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Effects of the Use of Millimeter Waves on the Statistics of Writer-to-Reader Delays in Military Communications Systems

W. Sollfrey

December 1980

A Project AIR FORCE report
Prepared for the United States Air Force

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PREFACE

This report represents the final documentation of the Project AIR FORCE study "An Analytical Basis for the Design of Usage Compatible Communication Systems." The study grew out of a Rand-supported project entitled "A New Approach to Millimeter-Wave Communications," described in Rand report R-1936-RC, April 1977. Fundamental background information and preliminary results were published in Rand report R-2473-AF, *Writer-to-Reader Delays in Military Communications Systems*, October 1979.

The present report conducts an extensive statistical analysis of delays in the AUTODIN I communications system. It determines how rain-induced outages in millimeter-wave earth-satellite links could affect the interstation transit delay and the total delay. Results are given for delays during rain periods and on an annual average basis.

This research evaluates the effects of millimeter waves in the proper context, by comparing them with other delay effects in the communications system. It should be of interest to analysts in the Air Force Communications Command, the Directorate of Space Systems and Command, Control, and Communications, and the Army Communications Command; to other government agencies concerned with satellite communications; and to groups involved in spectrum planning and management and future communications technology.

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SUMMARY

This report investigates the effect of the use of millimeter-wave satellites on certain military communications systems. We have argued in previous publications that the availability requirements as posed (99.9 percent or better) are unduly stringent for many communications purposes, and that rain outages, which act as an additional source of message delay, should be compared with delays in existing or proposed systems to evaluate their effects properly. This report contains detailed comparisons.

We study delays in the complete writer-to-reader message path, which includes outgoing administrative delays that occur while the message is being approved and delivered to communications headquarters, communications processing delays from the time the message is filed at the transmitting center until it is available for delivery at the outbox of the destination communications center, and incoming administrative delays between the time the message arrives at the outbox and its delivery to the final reader.

We treat in detail the AUTODIN I system. We have secured data from the Army Communications Command that give ground processing delays for over 450,000 messages, and data from the Defense Communications Agency that give interstation processing delays for over 5,000,000 messages. After performing an extensive statistical analysis on this message set, both for Flash or higher precedence level messages and for the complete set, we found that all time intervals can be well represented by broken-line lognormal distributions with very few changes in slope. There are no significant correlations between different intervals. The distributions for the total ground handling times were found directly from the data for outgoing and incoming messages, and by convolution processes we found the distributions for the total ground delay and for the total delay including interstation transmission. All these are also nearly lognormal.

The distributions show that the administrative delays, especially T_6, time awaiting pickup at the destination station, and T_7, the

destination local mail delivery time, provide by far the greatest contribution to the total delay, while T_4, the interstation transit time, provides by far the least. (For all delay definitions, see p. 8.) Efforts to reduce T_6 and T_7 would have much greater effect on decreasing the total delay time than would attempts to reduce the communications processing time or interstation transit time. If electronic deliveries were employed, even if only for unclassified traffic, the delays could be substantially reduced. This is the same conclusion reached in R-2473-AF, our previous publication, but is placed on a firmer foundation. We recognize there may be major cost and manpower problems.

The Flash delay distribution is severely skewed by a large number of outliers (messages with delays over eight hours in some time interval). These have been found to be almost entirely due to messages held overnight or through the weekend. Unless alternate message recipients are designated, there is no apparent way to improve this situation.

This investigation provides an empirical delay distribution on an existing military communications system. To ascertain how rain outages on millimeter-wave satellites affect this system, we have used the Crane model of rain attenuation (Refs. 6 and 7), and data collected by the Illinois State Water Survey (Refs. 19, 24, and 25). The Crane model enables us to determine the rain rate required to produce a specified fade depth on an earth-satellite link as a function of frequency, elevation angle of the line of sight, receiver characteristics, geographic location, and season of the year. We selected the four relevant frequencies (20, 30, 40, and 44 GHz), and used cooled paramp receivers. At each station of the AUTODIN study, we averaged over the seasons, weighting each by the fraction of the total annual rainfall which falls during that season. We then averaged over station location, weighting each by its fraction of the total traffic. The model then permitted us to compress the many parameters into just four values of rain rate which bracket and describe the conditions.

The Illinois Water Survey data provide rain rate measurements with intensity resolution of 0.1 millimeter/hour and time resolution of one minute. We determined from the data the distribution of rain duration at the four selected levels (1, 3, 7, and 20 mm/hr). These distributions also proved to be lognormal.

We combined the rain-induced delays and transit delays, and found that for Flash messages, the increase in transit delay is real and significant during rain periods, but only slight on an annual average basis. For the complete message set, the relative increase during rain periods is considerably smaller than for Flash, and the change is not significant on an annual basis. If we consider message total delays, combining ground, transit, and rain-induced, we find that the effect of the use of millimeter waves on the total delay for Flash messages is very slight during rain periods, and is negligible on an annual basis. The effect on the total delay for the complete message set is quite insignificant during rain periods and is indetectable on an annual basis. The results are quantified in the following table, where the percentiles represent the fraction of messages which pass in less than the indicated time.

CHANGES IN AUTODIN DELAYS

Delay Type	Percentile	Present AUTODIN Delay (min)	Worst-Case with Millimeter Waves	
			During Rain	Annual Average
Flash Transit	50	0.2	5	0.34
	70	0.5	10	0.7
	90	2.5	30	3.2
Flash Total	10	25	31	25.2
	30	45	53	45.2
	50	100	108	100.2
All Messages Transit	50	1	7.3	1.2
	70	3.3	16	3.7
	90	22	50	22.8
All Messages Total	10	11 hr	Not observable above 0.1 percentile	
	30	22.5 hr		
	50	36 hr		

For normal system operations, we would compare the total (ground plus transit) delays for a system employing millimeter waves, with attendant rain-induced outages, with delays in a system not employing them. Under crisis conditions, the ground handling delays could magically disappear. Since the crisis may occur at any time, we regard it reasonable to compare the annual average transit delays. Only for links that require instantaneous connection at all times, and can never stand any delay, should we compare transit delays during rain periods with the delays of the non-millimeter-wave system.

All these investigations, and the conclusions drawn therefrom, have been based upon a configuration that places millimeter waves in a most unfavorable light, with all system traffic sent through the millimeter-wave satellite links. System redundancy, proper location for ground stations, and the use of other communications media would reduce the effects of rain-induced delays considerably.

Certain military communications systems, such as dedicated command and control links, should not rely solely on the use of millimeter waves. For other systems, such as the mass traffic AUTODIN system, we believe that the analysis in this report demonstrates that the effects of rain on the distribution of delays are sufficiently slight, when considered in the proper context, that they do not provide a reason to forego the several advantages of millimeter waves.

ACKNOWLEDGMENTS

Many persons have contributed to this investigation. The research was conceived by N. E. Feldman, and numerous helpful ideas were provided by J. R. Clark and S. J. Dudzinsky.

The data used in this report were obtained with the help of Mr. J. King and Ms. M. Minor of the U.S. Army Communications Command, Lt. Col. Howell and Sgt. Larmi of the Air Force Communications Command, Lt. Col. Dobson and Sgt. Thomas of the Defense Communications Agency, and Dr. R. E. Semonin of the Illinois State Water Survey.

Computer programs for translation of the data into format suitable for the Rand computation system were written by M. M. Poindexter and J. Hull, and statistical analysis programs were prepared by M. D. Lakatos.

Valuable support was provided by the project monitor, Lt. Col. R. M. Crawford of the Directorate of Space Systems and Command, Control, and Communications. Finally, we wish to acknowledge the many helpful comments by the Rand reviewers of this report, G. B. Crawford and H. W. Wessely.

CONTENTS

I. INTRODUCTION

It has become clear that it will be necessary to expand military satellite communications systems into the millimeter-wave frequency region. Although this region extends nominally from 20 GHz to 300 GHz, practical considerations and frequency allocations will limit the useful part of the band, during the near and reasonable future, to the frequency regions 20.2 to 21.2 GHz (space-to-earth downlink), 30 to 31 GHz (earth-to-space uplink), 40 to 41 GHz (downlink), 43 to 48 GHz (either link), and 50 to 51 GHz (uplink). The Rand Corporation has been studying the theoretical and practical consequences of this expansion. A general discussion of the advantages and disadvantages of use of the millimeter-wave band appears in Ref. 1, and supporting analysis appears in Ref. 2.

Physical and electronic survivability can be enhanced, and interference and spectrum congestion alleviated, by the use of earth-to-satellite millimeter-wave links instead of the conventional microwave links. Nevertheless, concern about costs and rain outages has rendered communicators reluctant to exploit millimeter waves. During periods of sufficiently intense rainfall, the attenuation produced by the rain may make the link inoperative. It has been argued that every link must be required to have very high annual average availability, which forces the downlink to have so much satellite transmitter power available that it becomes economically unattractive.

In a previous publication[3] under this contract, the viewpoint was developed that for many communications needs these availability requirements are unduly stringent. A rain outage is equivalent to an equipment failure--both produce a delay in the transmission of messages. After the rain eases, the communications system can resume operation. We therefore argued that the additional system delay produced by rain outages should be compared with the delays that exist in present or currently planned communications systems. This comparison would provide a proper context for the rain effects, rather than comparing them with an arbitrary standard which may not be met at present. Reference

3 was designed to pose the general problem and provide the necessary background material to perform the comparison between present communications systems and systems employing millimeter waves, but the actual comparison was not conducted. The present report, which draws freely on Ref. 3, carries out the detailed operations and shows the effects of the use of millimeter waves on delays in certain communications systems. All discussions pertain to satellite links only.

We do not regard availability, which measures the total time during the year for which the system is operable, as an adequate index of system performance. Consider two systems with the same availability. If one has many short outages and the other a few extended outages, they will have quite different operational characters. If we wish to investigate the changes that could be produced in communications system operations by the use of millimeter waves, we should determine not only the effects on availability but also the effects on the distribution of delays. The main text of this report is devoted to a study of the delay distributions in a now-operational military communications system (AUTODIN) and then to determination of how these delay distributions would be affected if millimeter waves were used for the communications portion of the complete writer-to-reader message path. The analysis should not be regarded as a recommendation that millimeter waves should be used in this system, but rather as a careful consideration of the consequences that could result if they were used.

Since we do not wish to be considered blind supporters of millimeter waves, we shall consider the worst case situation in which the entire communications system employs millimeter-wave satellite communications links exclusively. In reality, a considerable fraction of the system would use other communications media, and redundancy and survivability considerations indicate that such links should continue operation. Hence, any favorable conclusions we may derive concerning millimeter waves are drawn from a position weighted against millimeter waves, and should be regarded as well-established.

As discussed in Ref. 3, there are several types of military communications systems. Certain links, such as the hot line to Moscow, require that instantaneous connections always be available. We would not consider millimeter waves for such circuits. Also, military communications satellites carry a mix of traffic of varying importance. Along with routine interstation traffic, for which an interruption need not be too serious, there may be such circuits as dedicated command and control links, which cannot be permitted to suffer any outages. Thus, either prospective millimeter-wave satellites must also carry conventional microwave links as well, or else current or new microwave satellites must be maintained in operation. These requirements for redundancy are to be expected. However, circuits of this essential character constitute only a very small p ion of the total number of circuits in the military communications system, and the benefits of millimeter-wave technology can be secured for the rest of the traffic if these special circuits are given special consideration. The special circuits can be operated via millimeter waves when it is not raining, and switched to lower frequencies or alternative media during rain intervals, thereby achieving the better of two possible worlds. Accordingly, we shall limit our investigation of delays to mass traffic systems, and not consider the dedicated circuits further.

Some systems, such as AUTOVON (AUTOmatic VOice Network), are of telephonic character, in that the message originator is connected directly to the recipient. The delays in such systems are determined by line availability and by the presence or absence of the recipient at his AUTOVON connection. According to Ref. 1, a study conducted at SAMSO in 1975-76 showed that their AUTOVON connection (33 outgoing lines) typically experienced several 10-minute blockages each day, and had blockages lasting three to four hours on as many as four days during the year. Thus, delays may be quite appreciable on these direct paths, availability is probably not better than 98 percent in a 24-hour day, and millimeter-wave systems, which suffer short outages due to rain, should not be dismissed offhandedly.

There are other military communications systems for which the communications path is more complicated than a direct link from originator to recipient. These involve the transmission of written or recorded information, either narrative text or data. The message is prepared by the writer, must generally receive approval, and is then delivered to communications personnel who process and transmit the message to the recipient's base. It may then undergo further processing, await pickup, and finally be delivered via local mail service to the addressee(s). Each of these procedures may involve delay. Communications systems of this type carry the bulk of U.S. military message traffic.

We have selected a particular system of this last type, the AUTOmatic DIgital Network (AUTODIN I) for our primary investigation of message delays. AUTODIN I, which is managed by the Defense Communications Agency (DCA) through a Deputy Director of Operations, constitutes the backbone for the transmission of military long-haul message traffic. It does not use millimeter waves. Extensive data have been collected on delays in AUTODIN I, although there are comparatively few published results.

AUTODIN I will be gradually replaced by a new generation "integrated service/agency automated message processing exchange" (I-S/A AMPE) now under development. According to current plans, AUTODIN II, the nominal successor to AUTODIN I, will be used to augment the DoD bulk data switching capacity. The impact on queueing delays of these changes is unpredictable, since the higher speed service may attract more traffic.

The Army Communications Command at Fort Huachuca, Arizona, conducted an exercise from March 1975 to June 1976, generally called ACCWRS (Army Communications Command Writer-Reader Study). This study collected data on the delays involved in all ground processing operations in certain stations of the AUTODIN I system during the period. About 1,887,000 records were collected.* Reports published on this study include Ref. 4, a general description of the study, and Ref. 5, an analysis of the effect of precedence. Also, on the first Thursday of each month the Defense Communications Agency collects and

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*Reference 3 cites this number as 1,662,000. However, we found after the publication of Ref. 3 that the messages for the final quarter of the study (April to June 1976) had not been included in the message total. The tapes used for the analysis of the present report contain the full set of messages.

subsequently publishes information on the speed of service of the communications portion of the writer-to-reader path for the entire AUTODIN I system. The data of Refs. 4 and 5 and for a single day (1 July 1976) of DCA records were used as the data base for the statistical analysis in Ref. 3.

We found on further consideration that this data base was too limited. Most of the analysis of Ref. 3 was devoted to messages of Flash or higher (referred to simply as Flash) precedence category. There were only about 60 outgoing Flash messages during the reporting period covered in Ref. 5, and only the mean and variance of the distributions of the several time intervals were given. At that time (1978) we asked the Army Communications Command to sort the data base to obtain the distribution. They further limited the data base to only one communications center and used a 15 minute time bin size. This left only about 15 outgoing Flash messages, although there were nearly 500 incoming Flash messages. We do not regard this as an adequate sample, either in numbers of data points or in time resolution, to perform a statistical analysis comparing delay characteristics with and without rain delays. Accordingly, we requested and received copies of the original tapes, which contain 1,887,000 records, and have used this much more complete data base for our analysis. We also requested and received from the Defense Communications Agency AUTODIN speed-of-service reports for a full year (June 1977 to May 1978), which provided our data base for the communications transit delays.

Section II gives our statistical analysis of the data. It was demonstrated in Ref. 3 that the distributions of the seven time intervals which characterize the total delay are highly skewed, and that the data are not well represented by a normal distribution. We show that the several intervals are well represented by broken lognormal distributions, with changes in slope which correspond to end-of-day effects. We investigate correlations among the several time intervals and show that they are all negligible. The outlier population (Flash messages with very long delays), which was treated in a rather ad hoc manner in Ref. 3, is considered further, and it is shown that virtually all outliers can be attributed to a very small number of very reasonable causes (misdating, messages kept overnight or over weekends or holidays, or simply missing the morning mail pickup). We have obtained directly from the data the distributions for each of the time intervals, and for the total ground handling time of outgoing and incoming messages. The distribution of the total writer-to-reader delay, including the ground and transit parts, is found by convolution of the outgoing, transit, and incoming delay distributions. All combined distributions are approximately piecewise lognormal. Results are presented for Flash precedence and for the complete message set. Delay distributions for Operational Immediate, Priority, and Routine precedence categories are shown graphically in the Appendix.

In Section III, we return to the subject of millimeter waves. As described in Ref. 2, the performance degradation of a millimeter-wave link produced by rain is caused both by attenuation of signal and increase of noise. These effects are functions of frequency and of receiver characteristics. To obtain the total effects on an earth-satellite uplink or downlink, we have employed the theory developed by R. K. Crane.[6,7] Crane's theory determines the attenuation produced by rain on a millimeter-wave link as a function of frequency, rain rate, path elevation angle, season of the year, and location on earth (divided into several zones). The theory may be inverted to determine the rain rate required to produce a specified attenuation. We then wish to determine the distribution of the duration of rainfall exceeding the indicated level. Several such distributions may be required to describe the complete problem. We have obtained data from several sources, most prominently the Illinois State Water Survey, and find that they also are approximately lognormal.

In Section IV, we combine the rain-induced delay distributions of Section III with the AUTODIN delay distributions of Section II, to obtain the effect on the delay distribution that could occur if millimeter wave links were used in the AUTODIN system. Again, approximately lognormal distributions are obtained. Conclusions are presented in Section V.

It is found that by far the most important causes of delays in the AUTODIN I system are the ground handling delays, which are unaffected by the use of millimeter waves for communications. Rain outages on millimeter-wave links produce significant additional transmission delays for Flash messages during rain periods, but only slight effects on the annual average delays. The effect of rain outages on the combined ground and transmission delays of Flash messages is very slight during rain periods and is indiscernible on an annual basis. All rain effects on the message delay distribution including all precedence levels are negligible.

We have not considered any problems of millimeter-wave satellite design, nor do we treat cost problems. Our results should be regarded as an indication of the effects on the delays in a military communications system which could result if millimeter waves were used to replace all its existing links between switching nodes. System redundancies, including terrestrial and cable circuits, tend of course to mitigate these effects. We consider it most gratifying that the changes in delays, at least in the particular military communications system we have treated, prove to be small when treated in full and appropriate context.

II. STATISTICAL ANALYSIS OF AUTODIN I

DESCRIPTION OF THE DATA BASE

We first describe the writer-to-reader path, following the text of Ref. 3, pp. 5-7. The complete path is shown in Fig. 1, which indicates who has the message at various times in the process, with a set of definitions of times and time intervals. First, within the originating headquarters, the message writer composes the message, prepares an initial list of addresses, and has the message typed. The next step, message approval, may involve considerable coordination at several approval levels. From Fig. 1, the first time interval, T_1, coordination and approval, begins with the completion of the draft message by the writer and ends with final message approval. The message then moves from the outbox of the final approving office to the inbox of the Telecommunications Center (TCC) at the originating headquarters.

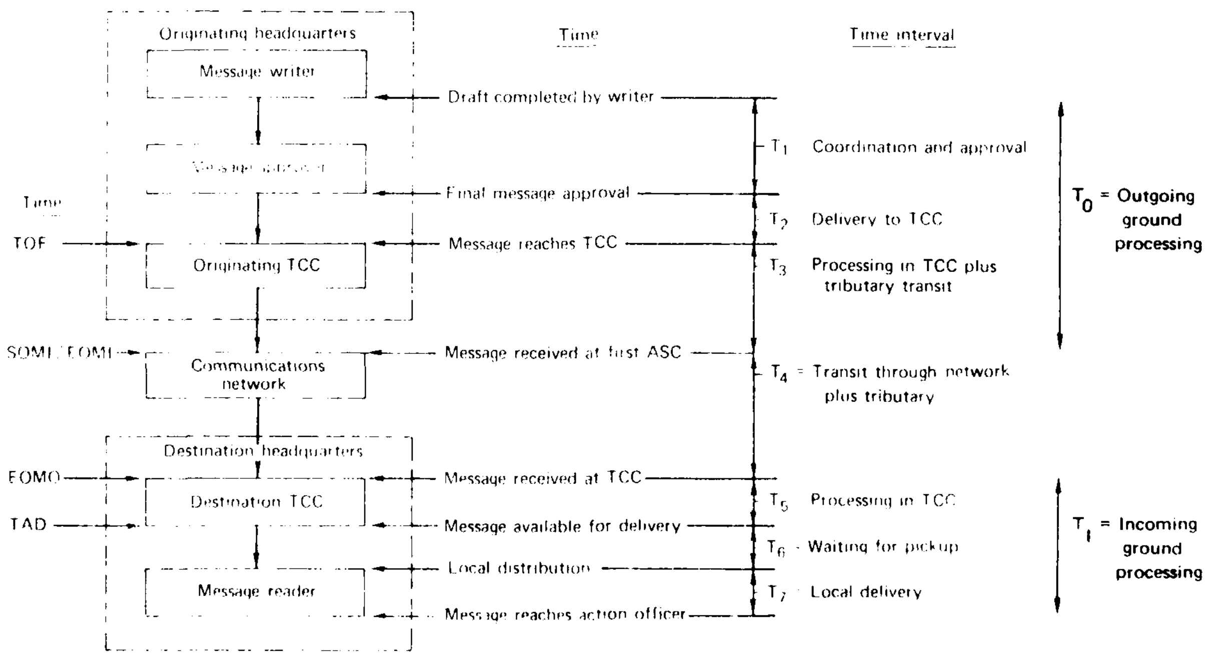

Fig. 1 Writer-to-reader time intervals

This delivery time interval is shown in Fig. 1 as T_2. Together T_1 and T_2 constitute the outgoing message administrative handling time.

At the TCC, the message is marked with a time of file (TOF), retyped if necessary, and routing indicators added for each address. It is converted into an electronic signal and forwarded via the tributary circuit of the originating TCC to the first Automatic Switching Center (ASC) of the interstation communications system, where it is momentarily stored as it joins the message queue. The time of arrival at the first ASC may be measured by either the start (SOMI) or end (EOMI) of the message signal. The interval from first arrival at the TCC to arrival at the ASC defines the outgoing processing time T_3. The message is then transmitted over the interstation network to the destination ASC. Several intermediate ASCs may be involved in the transmission process. The message travels via another tributary circuit from the destination ASC to the destination TCC, where it is reconverted to hard copy. Messages are confirmed and acknowledged link by link within AUTODIN. The network transmission time, T_4, measures the interval from arrival at the first ASC to reconversion at the destination TCC. The end of T_4 is identified as EOMO, end of message out. The destination TCC performs any further required processing, and marks the incoming hard-copy message with time av.ilable for delivery (TAD). This additional processing time is measured by the interval T_5. Collectively, T_3, T_4, and T_5 form the communications processing time.

The message is placed in the outbox of the TCC, awaiting delivery via interoffice mail to the headquarters of the addressee(s). The time spent waiting for pickup is measured by the interval T_6. Finally, the message moves via local delivery, such as the base mail service, to the addressee's headquarters, then by another delivery step to the office or desk of the individual addressee. The time for these delivery processes is measured by T_7. The administrative processing time at the destination is the combination of T_6 and T_7.

In addition to these seven sequential time intervals, there are two additional intervals. These are the total ground processing times for outgoing and incoming messages, and are defined as:

$$T_0 = T_1 + T_2 + T_3 \quad (1a)$$

$$T_I = T_5 + T_6 + T_7 \quad (1b)$$

The times T_0 and T_I measure how long a message spends in ground handling procedures, while T_4 measures the time spent in actual interstation communications. The ground handling times would be unaffected by the use of millimeter waves for communications. All the direct effects of rain-induced outages appear as changes in T_4.

The AUTODIN I system contains 15 ASCs and approximately 80 Inter-switch Trunks (ISTs), mutually connecting the ASCs. It is worldwide in scope, and uses a variety of communications media. There were about 765 TCCs in February 1977, and on an average day the volume of traffic was about 300,000 messages entering and leaving ASCs via ISTs, plus about 100,000 messages which go from a TCC to an ASC to a TCC connected to the same ASC. The system is further described in Ref. 3, pp. 8-16, and in Refs. 8-10.

As discussed in the Introduction, the Army Communications Command conducted an exercise known as ACCWRS to evaluate the AUTODIN processing time characteristics. At each station, outgoing messages were marked with time indicators from which T_1, T_2, and T_3 could be determined, and incoming messages were marked to determine T_5, T_6, and T_7. The exercise, conducted from April 1975 to May 1976, involved 13 Army TCCs located throughout the world. Since an outgoing message could go to, or an incoming message arrive from, a TCC other than one of the specified 13, a message could not be traced through its entire path. Thus, the study provided no measurements of T_4, and there is no correlation between messages of the outgoing set and messages of the incoming set. The set of incoming messages is much larger than the set of outgoing messages, especially for high precedence traffic, indicating the large number of possible sources for such messages.

We have obtained copies of the ACCWRS data tapes, which contain a total of about 1,887,000 records. The information in a single record is presented in Table 1, extracted from Ref. 5, which describes the data and the field size and type (10N = 10 numeric characters, 7A = 7 alphabetic characters, etc.). Most items are self-explanatory. The office symbols are coded to conceal the identification of the stations, but presumably the same symbol for a given station is used throughout the study. The message type is narrative (N) or data (D), the precedence level is Flash or higher (Z), Operational Immediate (M), Priority (P), or Routine (R). (Letters are those used on the tapes.) The classification is Top Secret (T), Secret (S), Confidential (C), Encoded for Transmission (E), and Unclassified (U). No Top Secret Flash precedence messages were found. The Zulu time is in hours and minutes on a 24-hour clock, and the elapsed time is in hours and fractions of an hour. The day of the week begins with 1 = Sunday.

The elapsed times are accurate to the nearest minute. However, we found upon examination of the data that there are strong concentrations at five-minute intervals, especially in T_1 and T_7. Since all the times were originally hand-recorded, either on special message forms or on slips fastened to the message, we assume this "five-minute quantization" effect represents the tendency of personnel to look at their watches, which in 1975-76 would have had hands rather than digital readout, and write down the time to the nearest five minutes. The effect is most pronounced for short time intervals. Thus, for the complete ensemble of messages, 330 had T_1 of four minutes, 6881 had T_1 of five minutes, and 241 had T_1 of six minutes. This is clearly an artifact of the message recording system, and it must be smoothed out in the statistical analysis. This effect is shown graphically later in the text in Fig. 7.

Our data for all intervals except T_4 came from those tapes. The T_4 data were obtained from the speed-of-service records provided by the Defense Communications Agency, as discussed in the Introduction. These records show, for a given day, the number of messages handled in 2, 4, 7, 10, 15, 20, 30, 60, 90, 120, 180, 360, and over 360 minutes, breaking the numbers down by precedence category. Twelve such records were obtained from the DCA, covering the period June 1977 to May 1978, and we had in our possession three records from 1976. This set of 15

Table 1

DATA DESCRIPTION

Field		Description	Size/Type
1		Message Routing Slip Number	10N
2		Routing Indicator	7A
3		Message Serial Number	
	a.	Type or Open Field	2AN
	b.	Station Serial Number	4N
4		Office Symbol	14AN
5		Message Type	1A
6		Message Precedence	1A
7		Message Classification	1A
8		Date Time Group	
	a.	Day	2N
	b.	Zulu Hour	4N
	c.	Letter Z	1A
	d.	Month	3A
	e.	Year	2N
9		Control Date	
	a.	Day	2N
	b.	Month	3A
	c.	Year	2N
10		Time Period (T_i)	1N
11		Elapsed Time (hours)	10N
12		Day of Week	1N
13		Julian Control Date	
	a.	Year	2N
	b.	Day	3N
	c.	Zulu Hour	4N

daily records, containing about 5,000,000 messages, constituted our data base for T_4.

Of the 1,887,000 records contained on the tapes, a few were blank and others were obviously incorrect, having delays of months. We eliminated these using the criterion that any delay over five days is erroneous. About 400 absurd records were eliminated by this criterion. The remaining data are regarded as reliable except for possible mis-dating of messages. We return to this point later.

There remains the question of whether the recorded message delays represent the actual message delays. If a message is of Flash or higher precedence level, an operator at the destination TCC may call the addressee and request that the message be picked up immediately. Under certain circumstances, the operator may read the message over the telephone. Expedited delivery of a hard copy may or may not occur. If it does not, then the destination administrative processing time will appear anomalously long compared with the actual speed with which the system functioned. Unfortunately, there is no way to determine from the data whether the message was telephoned as well as delivered, and the only practical choice is to accept the indicated delays as being the actual delays. If the telephone transmission, if any, had been recorded, the effect could have been included in the investigation, but there is no point in decrying the experimental design five years later.

With the data base as described, we now proceed to a statistical analysis of the delays experienced by messages of Flash or higher precedence category. Analysis of the complete message ensemble follows. The Appendix provides curves of the delay distributions for Immediate, Priority, and Routine messages, which we did not analyze.

ANALYSIS OF FLASH MESSAGES

The first operation was to sort out the Flash messages (throughout this report the term Flash refers to Flash or higher precedence level). A computer program selected on Character 39 of the record entries to extract the Flash messages from the great body of data. The selected messages were rerecorded as a working subset so the extraction would not need to be repeated. After the delays of over five days had been removed, a total of 2951 Flash records were found, 332 pertaining to outgoing messages and 2619 to incoming messages. Some messages had a record of only one time interval, some had two. There were complete records (three time intervals) for 87 outgoing messages and 640 incoming messages. Table 2 shows the number of records for each time interval.

Table 2

NUMBER OF FLASH MESSAGE RECORDS

Time Interval	*Number of Records*
T_1 - Approval	101
T_2 - Delivery to TCC	115
T_3 - Processing in originating TCC	116
T_0 - T_1 and T_2 and T_3	87
T_5 - Processing in destination TCC	980
T_6 - Waiting for pickup	829
T_7 - Local delivery	810
T_I - T_5 and T_6 and T_7	640

The data were then processed to obtain the delay distribution. The spread in the time intervals was very large, so it was not practical to use a constant size time resolution. Instead, the following set of time bins was used: from one minute to 180 minutes (three hours), one minute resolution; from three hours to six hours, five minutes; from six hours to 12 hours, 10 minutes; and one hour bins thereafter. The data were passed through this sieve, and the number of records in each bin was found for each time interval, as well as the cumulative distribution (number of messages whose delay does not exceed the specified value). For messages having all three records, the total ground handling time T_0 or T_I was also found and its distribution obtained.

At this point, we decided to attempt to eliminate misdated messages. A record was regarded as misdated if it differed by only a few minutes from a multiple of 24 hours, especially if the records of the other time intervals associated with the same message were short. Since the data set was not too large, we printed and examined the complete set of records. A total of 37 probably misdated records was found, arranged as indicated in Table 3.

Table 3

MISDATED MESSAGES

Interval	24 Hours	48 Hours	72 Hours
T_1	1	1	
T_2	4	1	
T_3	4		
T_5	5	1	1
T_6	10	1	4
T_7	2	2	

These records were "corrected" by subtracting the offending hours and assuming the minute indications in the records were correct. They were then placed in the appropriate bins. An alternative would have been to eliminate these records altogether. We decided to modify and retain the data, but do not wish to defend the decision.

The next step was to graph the distributions, which immediately raised the question of the proper choice of variables and scales. We chose to use probability paper, which is so constructed that a normal (cumulative) distribution plots as a straight line. The observed proportion of delays that exceed the abscissa was placed on the ordinate (probability) scale. Since the probability that the delay exceeds the abscissa is large for small values, the curves descend as the abscissa increases.

When the curves were plotted with the time delay itself as abscissa, covering the wide range one minute to four days, the curves descend so rapidly that the structure of the distribution cannot be ascertained. Accordingly, the logarithm (base 10) of the time delay in minutes was selected as the abscissa (independent variable). The logarithm goes from 0 to 3.76 over the indicated time range, and the distribution is clarified for both short and long time delays. Also, it was anticipated from studies of delays in other types of communications that the cumulative distributions would be nearly lognormal, that is, the logarithm of the delay would be normally distributed. Thus, we expected fairly straight lines when we plotted in this manner, and this expectation proved to be correct.

The distributions for all time intervals except T_4 were obtained by the indicated procedures from the ACCWRS data. The distribution for the transit time T_4 was found from the DCA speed of service records, which give the number of messages transmitted in less than a specified time, categorized by precedence level. These were converted to percentages for each of the 15 days of records, then the percentages averaged [illegible] days. The spread about the mean proved to be very small. [illegible] variation in the distributions, although the data include [illegible] in 1976 and a stretch of 12 months in 1977-1978, makes it [illegible] use the mean distribution for T_4 in conjunction with the [illegible] for the other time intervals, despite the fact that the ACCWRS [illegible] data were collected at somewhat different times. Figure [illegible] the distributions for T_4 for both Flash data and for the overall message set. The curves denote the averages over the 15 values, and the vertical bars indicate the spread from the smallest to the largest value. The curves are practically straight lines over the entire time range, and although the spreads look large, they occur at very low probabilities and correspond to just a few messages. (The DCA records show an average of about 2000 Flash messages handled per day. At the 1 percent level, this is only 20 messages, so the day-to-day

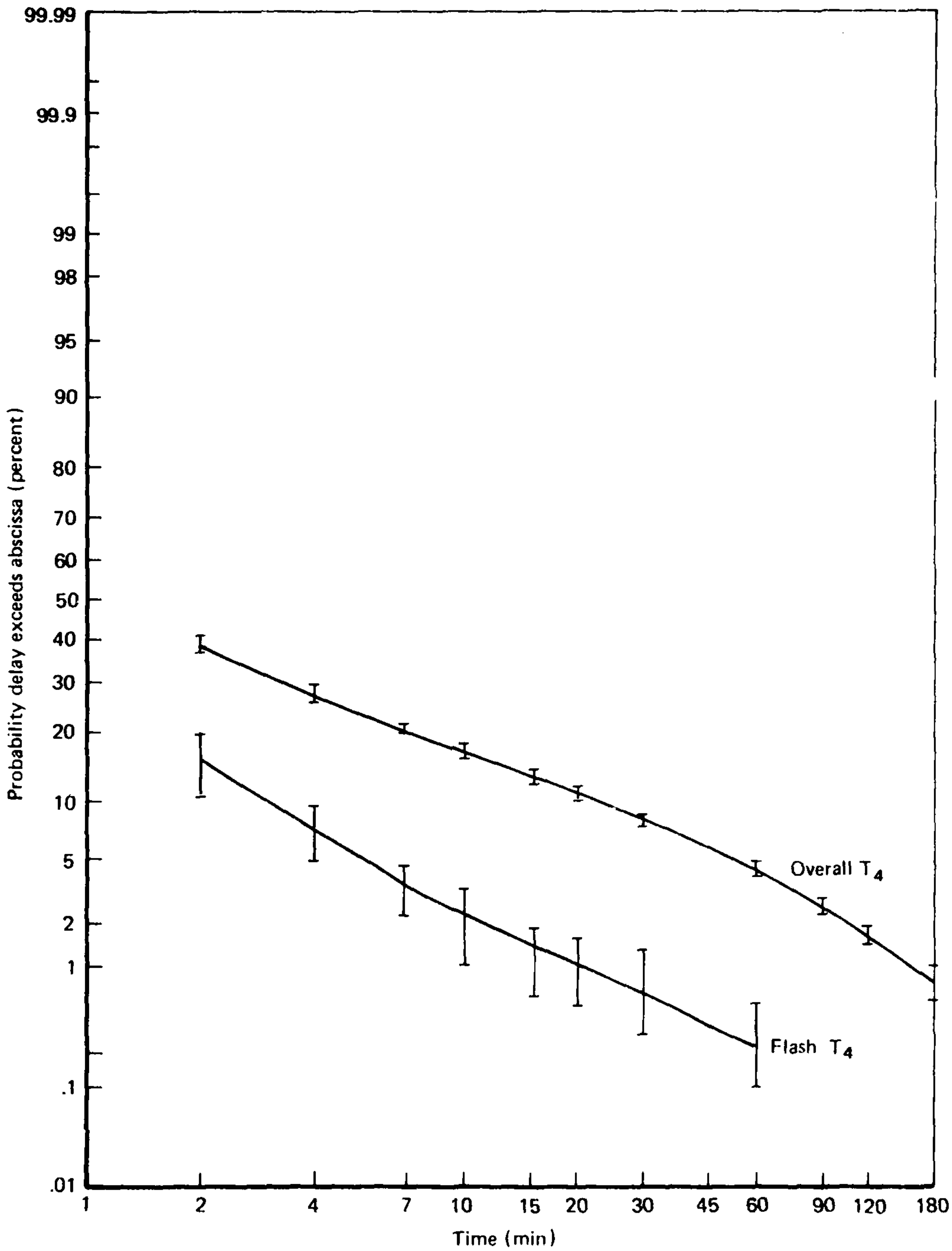

Fig. 2—Probability distribution of transit times

variations at 20 minutes delay correspond to fluctuations of only about 10 messages per day.) The use of the average curves appears perfectly satisfactory. There are a total of about 31,000 Flash messages represented, and a grand total of about 5,000,000 messages in the complete data set.

The data for T_4 displayed in Fig. 2 cover the time span from two minutes, the shortest time for which there is information, to three hours, the longest delay for which the results are trustworthy. Figures 3 and 4 give the delay distributions for the other time intervals, as extracted from the ACCWRS tapes. Figure 3 includes data for outgoing Flash messages, with the intervals T_1, T_2, T_3, T_0, and also T_4, whereas Fig. 4 represents incoming Flash messages, with the intervals T_5, T_6, T_7, and T_I. Data below the 1 percent level cannot be trusted, since too few messages are involved, so the curves are shown as dashed lines.

These curves are not as straight as those of Fig. 2, but the data can evidently be well represented by broken lines with no more than two breaks. The figures provide a large-scale view of the distributions. Detailed information is given as percentile levels, where the values represent the fraction of messages handled in *less than* T minutes, the opposite of the information on the curves. The percentiles are listed in Table 4, where, for example, the entry 2 for T_1 at 30 percent means that 30 percent of the messages were approved in no more than two minutes.

Table 4 is quite similar to Table 6, p. 28 of Ref. 3, which gives the percentiles of the Flash message distribution for one TCC for the April-June 1975 period with a time resolution of 15 minutes. However, the greater volume of data and much improved time resolution permits the drawing of many more deductions from Figs. 3 and 4 and Table 4 than could have been drawn from the earlier investigation.

We deduced in Ref. 3, p. 28, "the distribution of the actual data is severely skewed, that it is not well represented by a normal distribution, and that the mean delay is not a suitable measure for the speed of service of the system. Despite the large means, more than half the messages are processed in less than 15 minutes for each time interval. The communications system serves the majority of the users

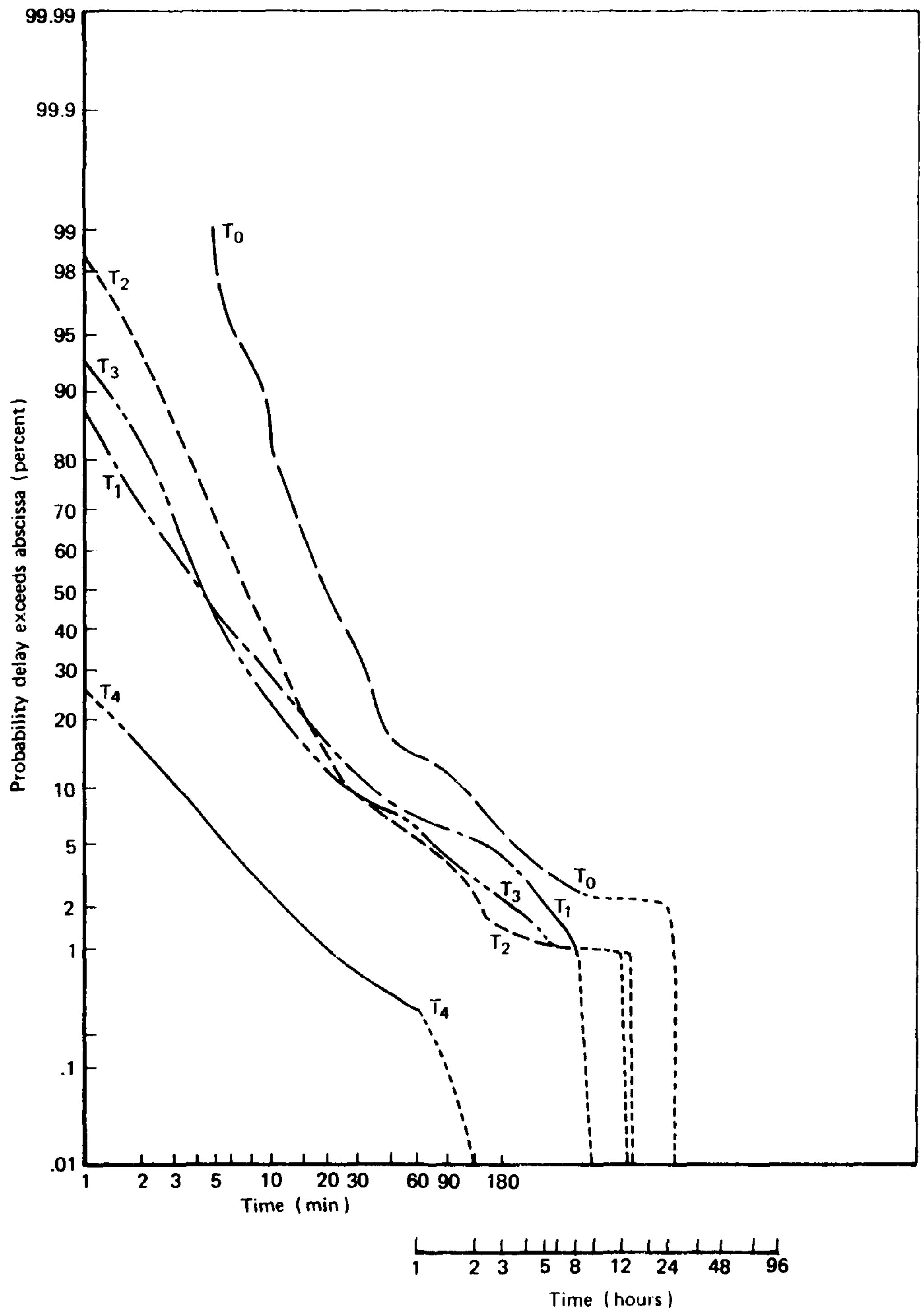

Fig. 3—Probability distribution of handling times—Flash messages

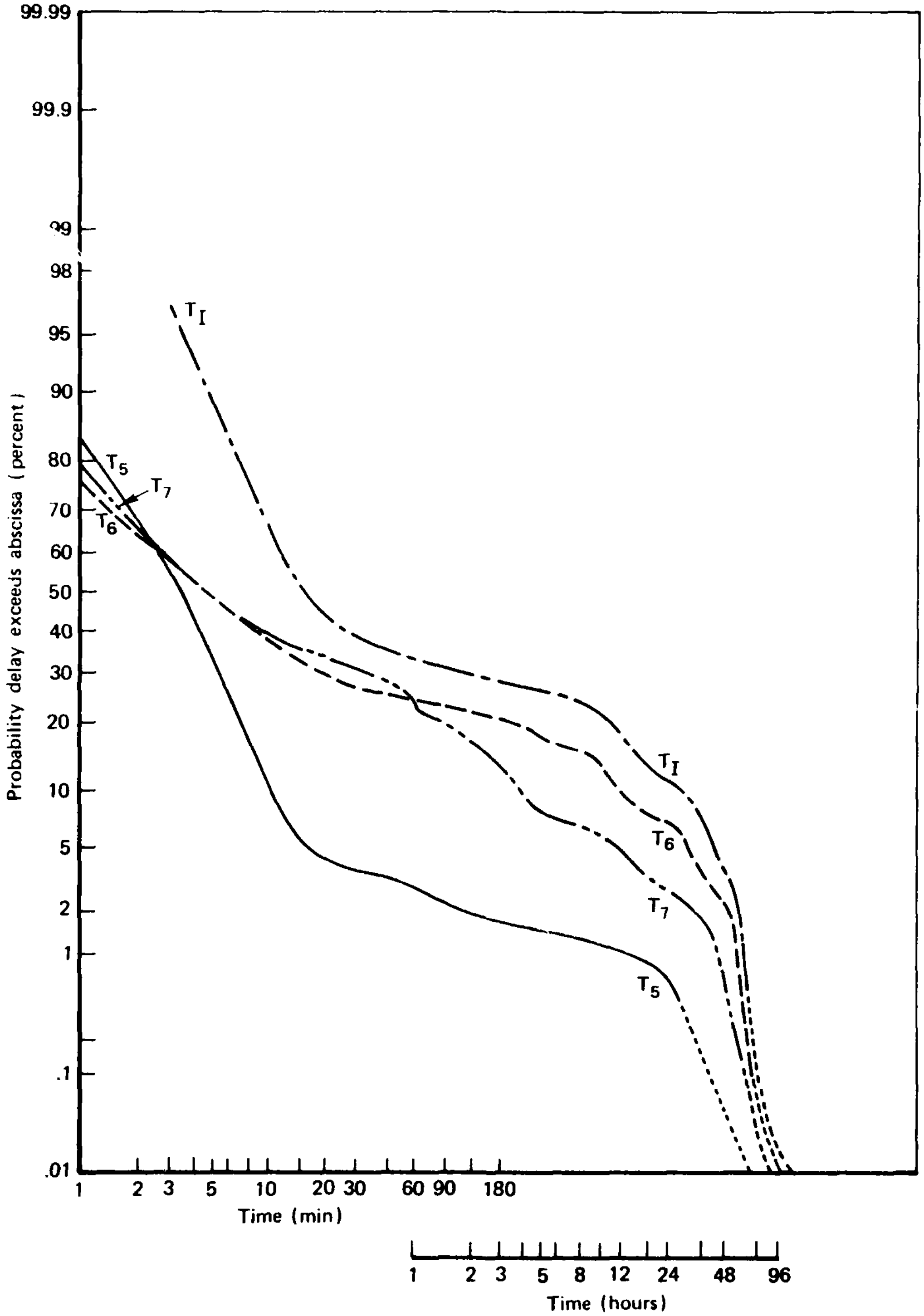

Fig. 4—Probability distribution of handling times—incoming Flash messages

Table 4

PERCENTILES OF FLASH MESSAGE DISTRIBUTION

Percentile	T_1	T_2	T_3	T_0	T_4	T_5	T_6	T_7	T_I
98	4.5 h	2 h	3.3 h	8 h	11	1.9 h	52 h	32 h	58 h
95	2 h	1 h	1.2 h	3.4 h	5	17	31 h	13 h	42 h
90	34[a]	26	25	1.7 h	3	11	12 h	3.8 h	29 h
85	20	19	15	51	2	8.5	8 h	2.4 h	16.5 h
80	14	15	12	38	1.3	6	3.2 h	1.5 h	12 h
70	9	11.5	7	33		5.3	20	33	1.9 h
60	5.5	9	5.3	25		4.3	9	9.5	28
50	4	7.2	4.2	20		3.5	4.5	4.5	16.5
40	2.7	5.7	3.5	15		2.7	2.7	2.7	11.5
30	2	4.7	2.8	13.5		1.9	1.5	1.7	9.5
20	1.5	3.6	2.1	10.5		1.2	.8	.9	7
10	.8	2.6	1.3	9					5
Mean	20	16	16	52	1.6	13	1.3 h	1.1 h	2.6 h

[a]All times in minutes unless specified in hours (h).

much better than would be indicated by the means." We see from Figs. 3 and 4 the nature of the true distribution as a set of broken-line lognormal distributions. From Table 4, we see that the mean lies near the 85 percent point of the distribution for outgoing messages, near 92 percent(!) for T_5, and near 75 percent for T_6 and T_7. The detailed structure is seen of the distribution for short delays. For example, the median delay is near four minutes for all ground delays except seven minutes for T_2. If we allow 15 minutes for each process, about 80 percent of the messages are passed through approval or delivery, 85 percent through outgoing TCC processing, essentially all through transmission, 93 percent through incoming TCC processing, 67 percent through awaiting pickup, and about 65 percent through final delivery. At these probability levels the three sources of delay for outgoing messages make approximately equal contributions. The transmission delay is short compared to everything else, and the processing in the incoming TCC is also rapid. Below the 65th percentile, awaiting pickup and final delivery are comparable to each other and are not particularly large. There appear to be changes in character at the break points of the distributions, and we shall address these shortly.

The information on total ground delays, T_O and T_I, is completely new. These quantities measure the time spent in all message handling procedures except transmission. Figure 3 shows that the ground handling time for outgoing messages drops in a fairly straight line (lognormal distribution) from the fastest handling (one message in 4.5 minutes) down to the 20 percent level (80 percent of the messages carried through the three procedures in 38 minutes). The slope then becomes much smaller, and the remaining messages take up to eight hours for the ground operations. The largest contribution to the delay for outgoing messages comes from the approval procedures. The change in slope of the approval delay distribution at 35 minutes probably means no more than the obvious fact that certain messages require more careful consideration for approval, and a half-hour is not sufficient.

A closer examination of the data for individual messages shows that there were two messages with unusually long delays. This pair occurred on the same day (Wednesday, April 23, 1975) and have the same office symbol. One had an initiation time (submitted for approval) of 0530, took 8 h 10 m for approval (1340), and 2 h 19 m for delivery (1559). The other was initiated at 1058, took three hours for approval (1358), and 5 h 54 m for delivery (1952). It may be that the approving officer was out for the morning and the delivery person was a substitute who misplaced the messages. This pair contributed 40 percent of the mean approval delay and 33 percent of the mean delivery delay, but clearly correspond to the only significant breakdown in handling outgoing messages.

The distributions for incoming messages are of a more varied character. As is to be expected, the handling times in the TCC, T_5, drop rapidly, and fully 95 percent are passed in 17 minutes following the lognormal curve. At this point, there is an abrupt change in slope, and it takes 15 hours to reach the 99 percent level. From Table 2, we see that the lower slope applies to about 50 messages. There is no apparent reason for this change in character. The awaiting pickup delays,

T_6, drop smoothly to the 25 percent level at 30 minutes, then slow markedly so the next 5 percent take up to three hours. The curve then steepens in a somewhat irregular fashion and descends to the 2.7 percent level at 52 hours. The T_7 curve stays close to the T_6 curve for times less than one hour, then drops markedly below, indicating that awaiting pickup takes significantly more time than delivery. Finally, the total handling time for incoming messages, T_I, at first drops rapidly to the 45 percent level at 20 minutes, corresponding to the rapid decrease of T_5, then slows and drops very slowly to the 25 percent level at eight hours. It then steepens and follows T_6, which makes the largest contribution to the total delay. We see that each curve can be well represented by no more than three straight lines, and such representation will be used when we compound the distributions.

We next ask, are there correlations among the intervals? These would determine interactions among different sections of the system. We define the normalized correlation coefficient between the intervals T_a and T_b as:

$$R_{ab} = \frac{\overline{T_a T_b} - \bar{T}_a \bar{T}_b}{\left[\left(\overline{T_a^2} - \bar{T}_a^2\right) \left(\overline{T_b^2} - \bar{T}_b^2\right) \right]^{1/2}} \qquad (2)$$

where the bars above the letters denote average value. We define a similar expression L_{ab} as the corresponding combination of products for the logarithms of the intervals. We calculated all the averages for the distributions of Figs. 3 and 4, and obtain the results shown in Table 5.

The correlation between intervals 1 and 2 appeared quite strong. However, we suspected this was because of the two unusual messages discussed above. The parentheses enclose the results when this pair of messages was eliminated from the distribution. The correlations among intervals or their logarithms now all appear small for all combinations except the logarithms of T_6 and T_7. We interpret this result as showing that for Flash incoming messages, those which are picked up rapidly are delivered rapidly, and those which spend a long time

Table 5

CORRELATIONS FOR FLASH MESSAGES

Outgoing					Incoming		
T	$R_{a,b}$		$L_{a,b}$		T	$R_{a,b}$	$L_{a,b}$
1,2	.552	(.144)	.430	(.245)	5,6	.003	.232
1,3	-.036	(-.057)	.059	(.008)	5,7	.052	.298
2,3	.020	(.096)	.203	(.174)	6,7	.185	.614

awaiting pickup also take a long time to deliver. These two operations are the only ones in the entire chain which are likely to be performed by the same personnel, so their correlation is reasonable.

We now discuss the outlier population, which we considered in Ref. 3 in a manner we now regard as inadequate. These messages cause the severe skewing and excessive system mean delays. With the misdated messages and the anomalous pair removed, there are no really significant outliers among the outgoing messages. For the incoming messages, we define an outlier as a message with any interval greater than eight hours. With misdates eliminated, there were 154 such records among the incoming records, or approximately 6 percent of the total number of incoming messages.

The records show day and time. Checking against the day of the week, we found many messages which had arrived late Friday, Saturday, or Sunday had not been delivered until Monday morning. Certain messages, those with the longest delays of all, arrived on holiday weekends. We next checked arrival hour, and found that a large number of messages which arrived in the late evening or early morning hours had not been delivered until the beginning of the next working day. A similar number also missed the morning mail pickup and were not delivered until the afternoon. One group of messages was the first set of Flash messages arriving at that particular office symbol and may reflect station startup. Three messages appear to have been lost in the mail, and there are two messages which we cannot explain.

Some of the records correspond to either multiple addressees or multiple copies of a single message. Three office symbols appear to share a common mail station, since they consistently display the same delays. We count these as single entries, which eliminates 26 records from the outlier cause set. There are 14 record pairs. The only difference is a minute or so of initiation time, with the messages arriving at the pickup box at the same time. We consider these to be either multiple copies or retransmissions, and count them only once. The outlier population thus consists of 114 messages for which we have all three time intervals. The probable causes and the mean total delays associated with each are shown in Table 6.

Table 6

OUTLIER POPULATION

Cause	Number	Mean Total Delay	
		Hours	Minutes
Ordinary weekend	44	38	50
Holiday weekend	8	59	15
Overnight	43	14	27
Missed morning pickup	7	12	40
Station startup	7	30	40
Lost in mail	3	64	48
Unexplained	2	20	48
Total	114	29	20

All these delays appear quite appropriate to their probable causes. We may conclude that the major causes of outliers, that is, delays that would be regarded as excessive for the transmission of Flash messages from writer to reader, appear to be natural consequences of the inability of the pickup and delivery system to function properly on nights and weekends. There is nothing mysterious involved, and no obvious method of eliminating the difficulty, except for the station startup problems, which would not be expected to recur.

As discussed earlier, it is possible that these long delays are not real, that the messages may have been transmitted by telephone.

However, it is not likely that the intended recipient would have been available during the night or weekend hours, unless he was expecting the message. Hence, we believe that the numbers in Table 6 are valid.

The curves in Figs. 2, 3, and 4 and the ensuing analysis have been derived directly from the data. We next consider some further distributions which require more complicated mathematical investigations. The intervals T_0, T_4, and T_I represent the delays produced respectively by handling at the originating station, transmission between stations, and handling at the recipient station. They are independent and sequential. The distribution of the sum of T_0 and T_I provides information about the total delay produced by the numerous ground handling procedures, T_G. The distribution of the sum of T_4 and T_G provides information about the total delay in the entire writer-to-reader path, T_E. We first show how to calculate these distributions, then determine and discuss them.

The distributions in Figs. 2 through 4 are cumulative distributions, representing the probability that the delay exceeds the indicated value. We denote the cumulative distribution for some variable T as F(T). The differential distribution, that is, the probability that T is between T and T + dT, is given by:

$$f(T)dT = -\frac{dF}{dT}dT \tag{3}$$

where the minus sign arises from our choice of decreasing distributions.

Suppose we have two independent variables, say T_1 and T_2, with the respective differential distributions $f_1(T_1)$ and $f_2(T_2)$. Then the differential distribution of their sum T_3 is found by letting T_1 take on an arbitrary value T less than T_3, which has the probability $f_1(T)$, requiring T_2 to have the value $T_3 - T$, which has the probability $f_2(T_3 - T)$, then integrating over T_1, yielding:

$$f_3(T_3) = \int_0^{T_3} f_1(T)f_2(T_3 - T)dT \tag{4}$$

Integrating this over T_3 gives the cumulative distribution:

$$F_3(T_3) = \int_0^{T_3} F_1(T) f_2(T_3 - T)dT \qquad (5)$$

where the subscripts 1 and 2 can be interchanged in Eq. (5).

The cumulative distributions of Figs. 3 and 4 may be fitted quite accurately by broken straight lines. If we had plotted the differential distributions directly from the data, we would have found rapid fluctuations, which arise from the time resolution of the measured values and are artifacts of the data collection process. These fluctuations are smoothed by replacing the actual differential distribution by the derivative of the fitted broken-line lognormal distribution. The lognormal distribution is represented by an error function,[11] its derivative by a Gaussian, as follows:

$$F(T) = \int_{x(T)}^{\infty} dz e^{-z^2} / \sqrt{\pi} \qquad (6a)$$

$$f(T) = b e^{-x^2(T)} / T\sqrt{\pi} \qquad (6b)$$

$$x(T) = a + b \ln T \qquad (6c)$$

The coefficients a and b are different for each broken-line segment of the distribution for each interval T.

The constants in the distribution for each broken section of the lognormal approximations are found by fitting lines to the curve by successive approximation to reduce the absolute error. We were able to reduce the departure of the fitted probabilities from the real probabilities to less than 0.5 percent, using no more than four linear sections. We then prepared a computer program to calculate the convolution integral of Eq. (5), inserted the fitted cumulative and differential distributions, and thereby obtained the cumulative distributions for the total ground delay T_G and the total delay T_E. The resulting distributions also were accurately fitted by broken-line lognormal distributions. The combined fitted distributions are shown in Fig. 5, with the sharp corners rounded. The imperfect agreement of the curves of Fig. 5 with those of Figs. 3 and 4 arises from the curve-fitting.

The combined distributions are clearly of the same character as their constituent distributions. The closeness of the distributions of the total ground delay (T_G) and the total delay (T_E) illustrates in a highly graphic way how little the transit time T_4 contributes to the total delay. The curve for T_E actually lies to the right of the T_G curve, but beyond 60 minutes the difference is too small to show on Fig. 5. We show an enlarged version of the first three hours of the curves in Fig. 6. The percentiles of the distributions of Fig. 5 are given in Table 7.

The lognormal character of the distributions implies that there are a large number of messages with long delays. Hence, we expect that the delay corresponding to a given percentile in the combined distribution will significantly exceed the sum of the delays in the constituent distributions at the same percentile level. This effect is shown very clearly in Table 7. The means are additive, so the mean of the combined distribution lies at a lower level on the distribution than the means of the constituents (85 percent for T_0, 72 percent for T_I, 61 percent for T_G). Above the 75 percent level, the combined distributions are controlled by the outlier population.

Figures 3 through 6 and Table 7 show how well the AUTODIN I system serviced Flash traffic at the time of the study. The ground delays are clearly the most important at all percentile levels. Outgoing and incoming delays are comparable below the 60 percent level, but the long waits for pickup and delivery cause the incoming delays to greatly exceed the outgoing at all higher percentile levels. The combined delays show that it takes about 80 to 90 minutes to process half the messages through the ground operations, but over 18 hours to get 80 percent of them through, and over two days to process 95 percent of them.

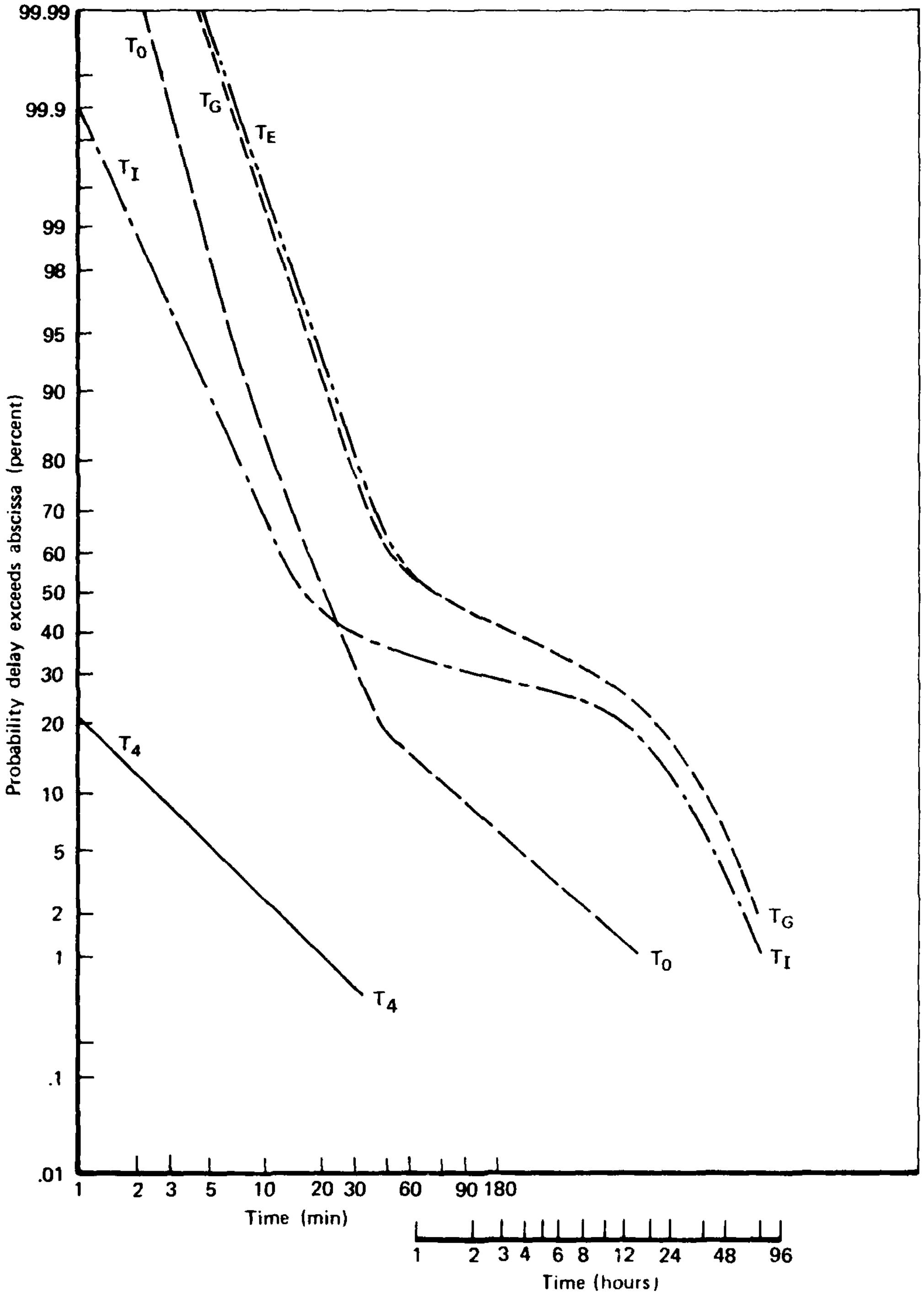

Fig. 5 — Probability distribution of combined handling times—Flash messages

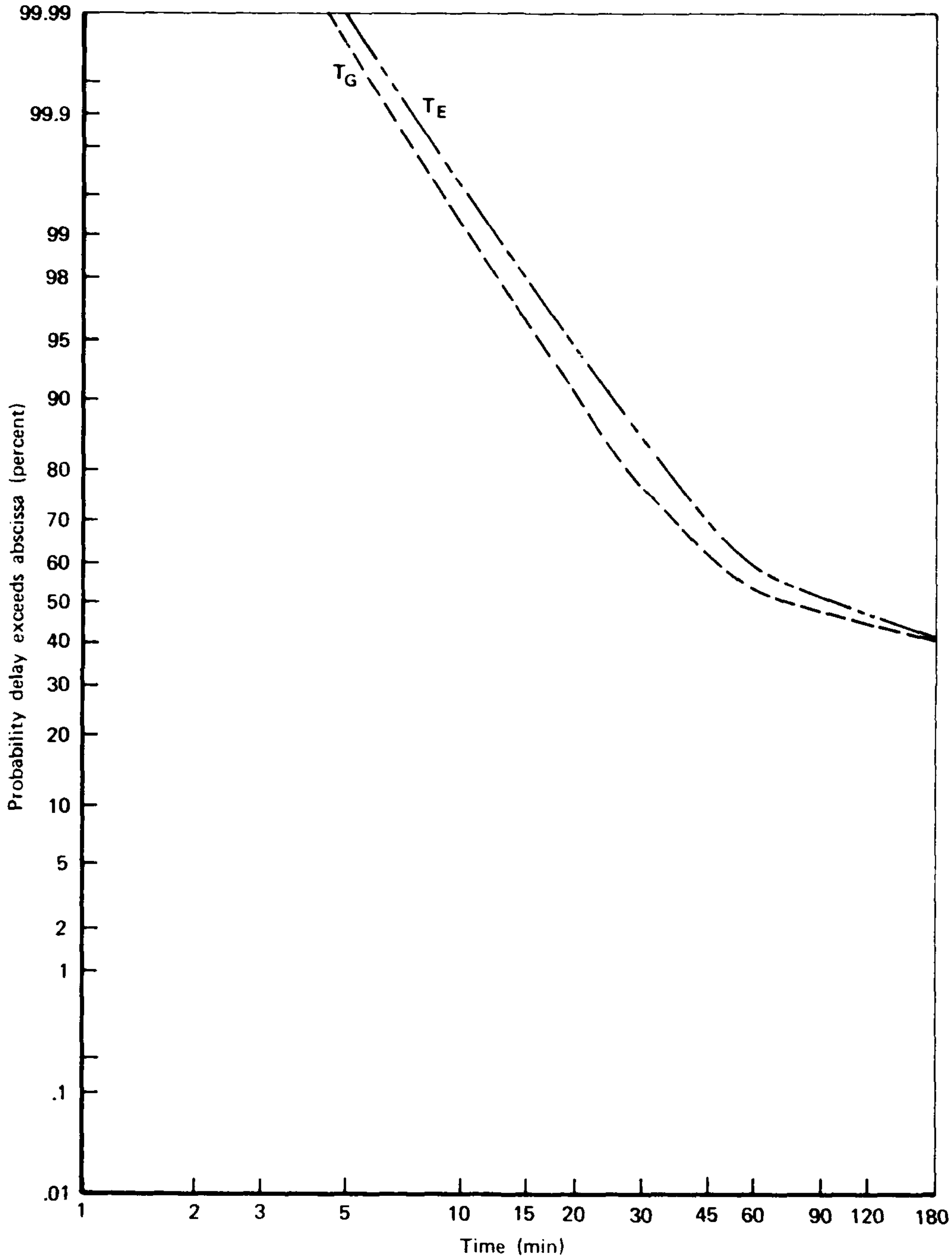

Fig. 6 — Probability distribution of early combined handling times—Flash messages

Table 7

PERCENTILES OF FLASH MESSAGE COMBINED DISTRIBUTIONS

Percentile	T_O, Outgoing Ground Delay	T_4, Transit Delay	T_I, Incoming Ground Delay	T_G, Total Ground Delay	T_E, Total Delay
98	8 h	11	58 h	65 h	65 h
95	3.4 h	5	42 h	49 h	49 h
90	1.7 h	3	29 h	36 h	36 h
85	51[a]	2	16.5 h	25 h	25 h
80	38	1.3	12 h	19 h	19 h
70	33		1.9 h	9.4 h	9.6 h
60	25		28	3.3 h	3.5 h
50	20		16.5	1.4 h	1.6 h
40	15		11.5	47	58
30	13.5		9.5	36	45
20	10.5		7	28	36
10	9		5	21	25
Mean	52	1.6	2.6 h	3.5 h	3.5 h

[a]All times in minutes unless specified in hours (h).

This completes our study of delays of Flash messages. We next consider, in a somewhat briefer fashion, the delays for the complete message distribution, which includes all precedence levels.

ANALYSIS OF THE COMPLETE MESSAGE DISTRIBUTION

We applied some of the procedures to the complete message distribution that we applied to the Flash distribution. Because of the very large number of messages and the expense of processing the data files on the computer, certain steps were omitted. We eliminated duplicate messages and those records displaying over five days' delay, but did not eliminate or correct misdated records. Hence, we expect that there is an excess of long delay messages. The total message set includes about 1,840,000 records after the elimination, among which there were approximately 156,000 with delays over 24 hours or about 8.5 percent of the total. If we count as misdated the excess of messages in the 24 hour time bin over the mean of the 23 and 25 hour bins, and similarly for 48, 72, and 96, we find a total of 3413 such messages, which is 0.185 percent of the total, or 2.2 percent of the long delay messages. We accept this number, since we do not attempt to draw conclusions of greater accuracy.

We first illustrate the "five-minute quantization" effect referred to earlier. Figure 7 shows T_1, approval time, and T_7, final delivery time, for the first hour of the distribution. In this figure, and this figure only, linear time and probability scales are used. These two time intervals show the five-minute quantization effect most strongly, but it is present in all the other intervals except T_4. There is a point on the curves at each minute, and the staircase character of the data is obvious. The effect continues, in a less pronounced magnitude, at longer delays. As mentioned before, we regard this effect as a paradigm of the propensity of personnel to record time to the nearest five minutes.

The number of records for each interval is shown in Table 8.

The cumulative distributions for the several time intervals are given in Figs. 8 (outgoing) and 9 (incoming). The staircase effect is quite apparent for T_1, T_6, and T_7, but does not appear in the other intervals. The logarithmic time scale smooths the staircase for times beyond one hour.

We see that the cumulative probability distributions for the complete message set are much closer to lognormal distributions than for the Flash message set. The delays in processing in the TCCs, T_3 and T_5, are almost perfectly lognormal over the entire time range from one minute to four days, and the transit time T_4 is also closely lognormal over its range of significance (two minutes to six hours), although it steepens at the later times.

The other intervals display interesting behavior. If we smooth out the staircase at the beginning, the distributions of T_1, T_2, T_6, and T_7 are quite accurately lognormal from one minute to eight hours, then they begin to display oscillations. We interpret these as end of day, overnight, and weekend effects. If we assume a nine-hour working day (we leave the validity of this assumption to the credulity of the reader), then we would expect that the distribution for the message

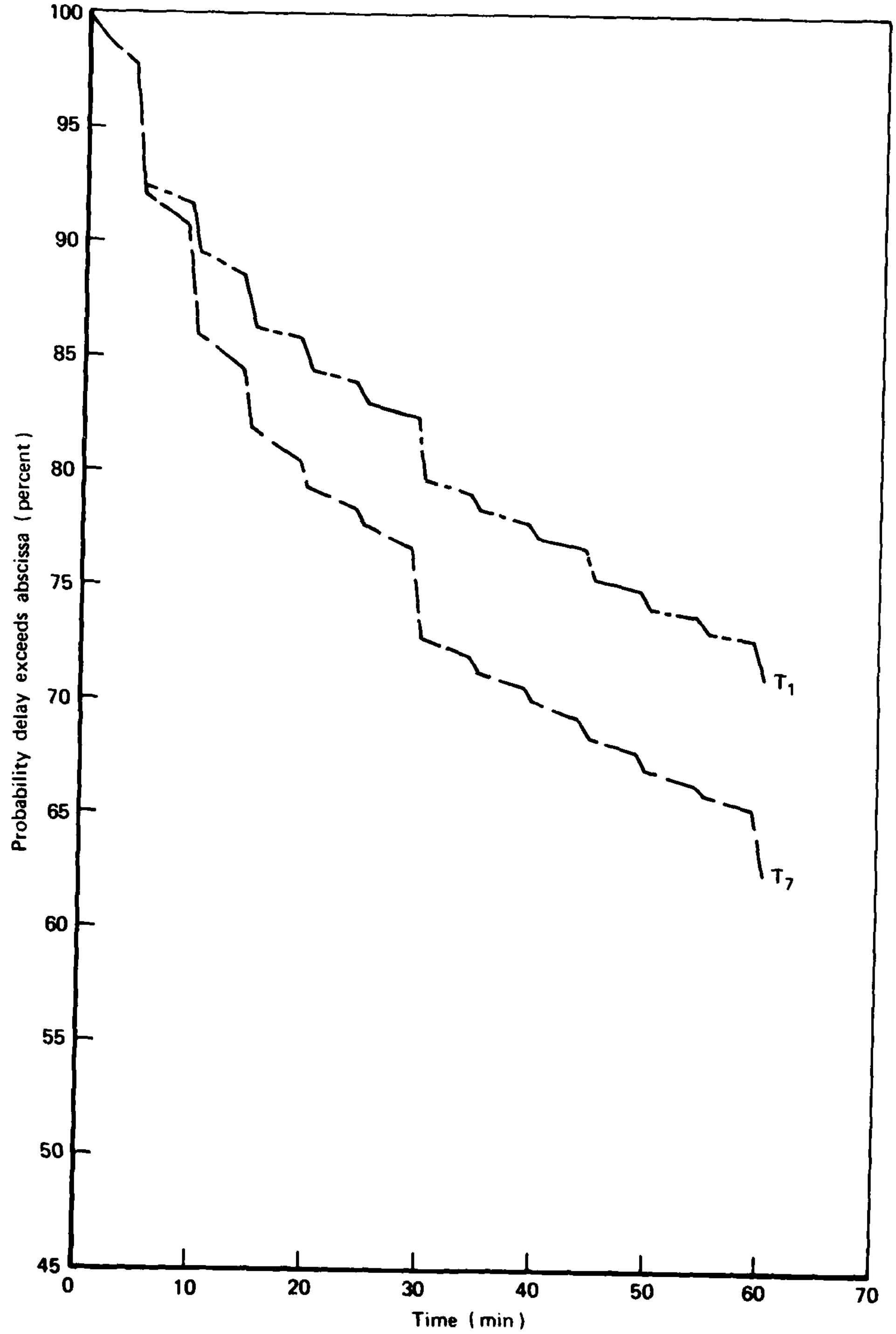

Fig. 7 — Five-minute quantization effect

Table 8

NUMBER OF RECORDS - ALL MESSAGES

Time Interval	*Number of Records*
T_1 - Approval	133,221
T_2 - Delivery to TCC	163,089
T_3 - Processing in originating TCC	168,389
T_0 - T_1 and T_2 and T_3	119,695
T_4 - Transit (from DCA)	~5,000,000
T_5 - Processing in destination TCC	467,445
T_6 - Waiting for pickup	463,427
T_7 - Local delivery	442,344
T_I - T_5 and T_6 and T_7	388,480

approval time, T_1, would flatten between about eight hours (end of day), and 18 hours (beginning of the next working day). It would then strongly steepen, as the messages that were not approved the previous day were treated, then flatten again. Messages which are held over weekends account for the sharp steepening of the curve near 62 hours (6 p.m. Friday-8 a.m. Monday). The time for delivery of messages to the TCC, T_2, should follow the same working-hours curve. These effects show very clearly in the distributions. Since the TCC operates on a 24-hour schedule, T_3 is free from these phenomena. The total ground-processing time for outgoing messages, T_0, displays the effects, but to a much lesser degree and later on the time scale. Since the total delay T_0 is formed by adding the constituent delays, delays in the 8 to 14 hour range will mostly involve combined delays from the working day. Thus, the end of day and ensuing effects should not be as conspicuous, and they should involve relatively long constituents, which causes them to occur later. As a matter of fact, the addition of constituents has smoothed the distribution sufficiently that T_0 is practically lognormal over the entire range.

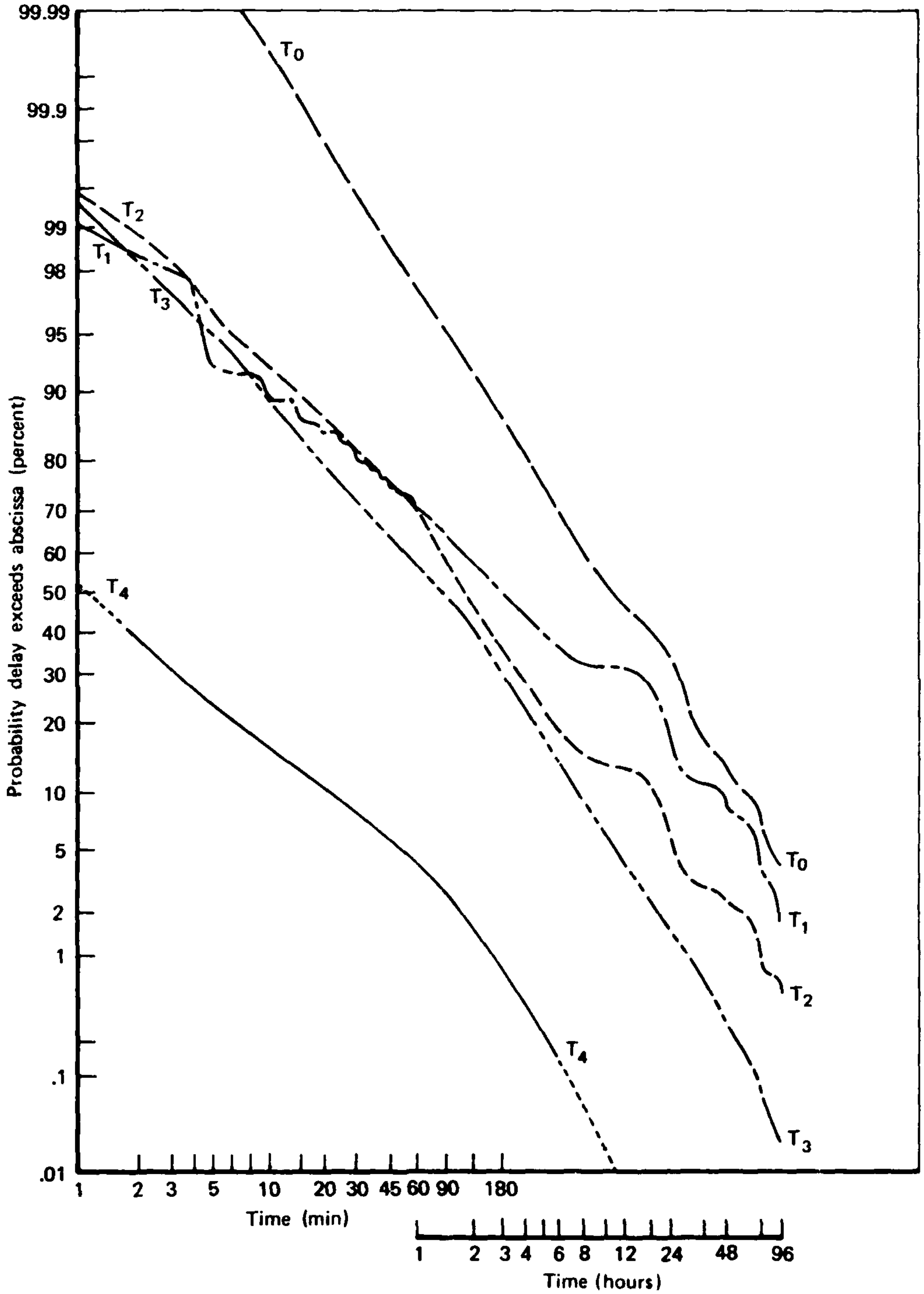

Fig. 8—Probability distribution of handling times—all outgoing messages

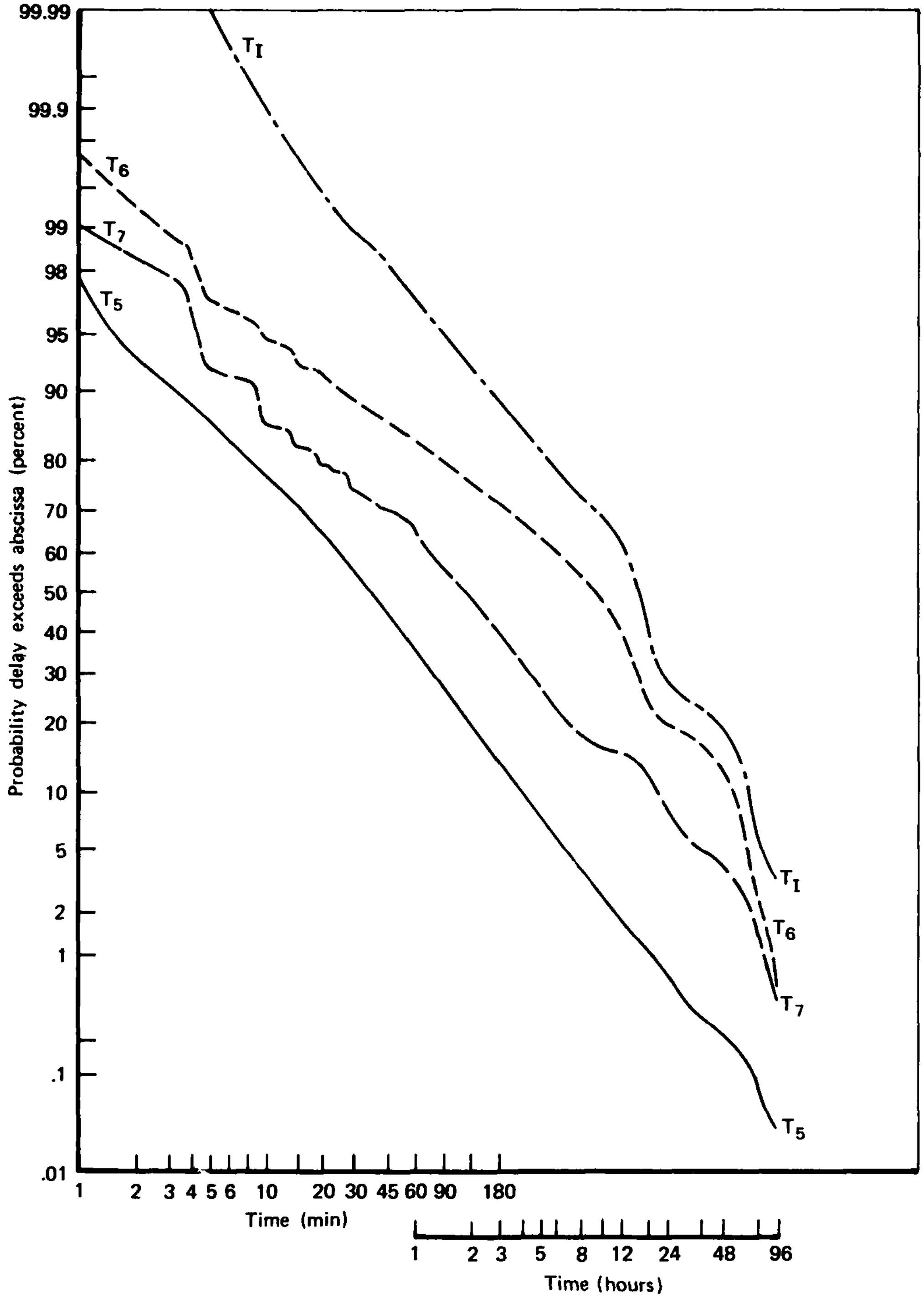

Fig. 9 — Probability distribution of handling times — all incoming messages

The behavior of the distributions of the time intervals for incoming messages is similar, but with significant differences. Again, if we smooth out the staircase at the beginning, T_5, T_6, and T_7 are closely lognormal to eight hours, and T_5 continues lognormal thereafter. Between eight hours and 18 hours, T_6 steepens and T_7 flattens. The latter effect is just like T_2 for outgoing messages, since messages do not get delivered during the nighttime. Those messages which have not been picked up by the end of the day will not be delivered until morning. However, the TCC continues to operate during the night, so many messages will be generated. This increase rather than decrease in the number of messages means that the steepening of the curve occurs at a much shorter delay than it did for outgoing messages, as is shown by the curve for T_6. We expect that most of these nighttime messages correspond to extensive data transmissions. The weekend effect near 62 hours is again apparent. The total ground delay for incoming messages, T_I, is somewhat more oscillatory than the outgoing delay T_0, but is nevertheless not too far from lognormal. We shall fit T_0 and T_I with broken-line lognormal distributions, as we did for the Flash traffic, but comparison of Figs. 8 and 9 with Figs. 3 and 4 shows that the changes in slope are not nearly as severe for the complete message distributions as they were for the Flash distribution. Whatever effect causes these distributions to be lognormal, it is clearly enhanced by the much larger number of messages included.

Table 9 gives the percentiles of the distributions for the complete message set. We can draw some deductions from this table, and compare them to our deductions about the Flash percentiles in Table 4. The percentiles of the total ground-delay distribution, which we will calculate and discuss in a few later pages, are shown in the last column of Table 9.

First looking at the outgoing data, we see that the approval time T_1 is the largest delay for times greater than one hour (30th percentile). This is appropriate, since more time should be devoted to approving messages, which requires thought, than to delivering them. For shorter time intervals, the approval time is comparable to the delivery and TCC processing times. These relations are exactly the same as for Flash

Table 9

PERCENTILES OF THE COMPLETE MESSAGE DISTRIBUTION

Percentile	T_1	T_2	T_3	T_0	T_4	T_5	T_6	T_7	T_I	T_G
98	95[a]	65	21	>96	1.7	11.5	79	69	93	
95	72	26	11.4	84	52 m	6.6	64	35	78	
90	44	19.5	7.5	61	22 m	4.0	56	20.8	65	
85	26	8.2	5.7	45	14 m	2.7	39	11.6	58	
80	23.5	5.8	4.6	33	7 m	2.0	22.5	6.9	44	81
70	17	3.9	3.1	26.3	3.3 m	1.3	15.5	4.1	23.3	59
60	5.1	2.7	2.1	20.7	1.9 m	52 m	12.5	2.9	18.8	46
50	3.1	2.0	1.4	11.1	1.1 m	36 m	9.3	2.0	16.8	36
40	2.0	1.4	56 m	8.1		25 m	6.1	1.2	13.0	29
30	1.1	56 m	34 m	6.1		16 m	3.3	40 m	9.5	22.5
20	30 m	33 m	20 m	4.3		8.5 m	1.4	20 m	5.6	17.5
10	10 m	15 m	10 m	2.6		3.5 m	27 m	9 m	2.8	11.0
Mean	13.3	5.3	3.0	20.6	10 m	1.9	16.0	7.7	25.6	

[a] All times in hours unless specified in minutes (m).

messages. It is noted in Ref. 3 that message length and precedence level are inversely correlated, that is, high precedence level messages are short and low precedence level messages are long. We would expect long messages to require additional time to peruse and approve, and the data for T_1 demonstrate this clearly.

We see from Table 9 that T_2 and T_7 have very similar distributions. Since they measure the efficiency of the ordinary mail delivery systems at the outgoing and incoming stations, we would expect them to be equivalent, and they are for the complete message set. For Flash messages, we would expect greater urgency on the outgoing portion. This is displayed rather strangely. For delays less than 10 minutes, the incoming messages are delivered more rapidly, and for all longer delays, the outgoing messages are delivered faster. If we visualize a running messenger, we conclude that he runs a longer time to deliver an outgoing message, which he received from a ranking officer, to his TCC, than he would run to deliver an incoming message from the conventional TCC outbox. Another possibility lies in the circumstance that the great majority of Flash messages originated at a particular TCC and went to two other TCCs. We may merely be seeing the relative efficiency for Flash messages of the mail systems at those TCCs, whereas the complete message set averages over all TCCs.

We observe that although T_3 and T_5 are consistently shorter than the other ground delays, T_3 significantly exceeds T_5 at all percentile levels for both the complete message set and for the Flash messages. This is reasonable because there are more operations to perform on a written message to enter it into the transmission queue than there are to extract it upon reception. Furthermore, the transit delay T_4 is much shorter than any of the ground delays, and is especially so for the complete message set as compared with the Flash messages (for example, at the 90th percentile, T_4 is 9 percent of the next shortest interval, T_5, for the complete set, whereas it is 27 percent of T_5 for the Flash set). Finally, T_6, the time spent waiting for pickup, is the principal cause of delay in the complete message set at all percentile levels. Clearly, efforts to reduce T_6 would have much greater consequences toward reducing the total delay than would efforts to reduce the other delays.

We calculated the correlations among the various time intervals, using the same procedures as for the Flash messages. Because of cost limitations, we only calculated the correlations for one of the three tapes on which we had stored the message set. This tape contained about 550,000 records comprising a total of about 29,000 outgoing and 123,000 incoming messages for which all three time intervals were available. The correlations among time intervals ($R_{a,b}$) and their logarithms ($L_{a,b}$) are shown in Table 10.

Table 10

CORRELATIONS FOR THE COMPLETE MESSAGE SET

Outgoing			Incoming		
T	$R_{a,b}$	$L_{a,b}$	T	$R_{a,b}$	$L_{a,b}$
1,2	-.0042	.057	5,6	.043	.099
1,3	-.0042	.036	5,7	.064	.233
2,3	-.0084	.070	6,7	-.036	-.016

All these values are quite small except for the logarithms of T_5 and T_7. To test the hypothesis that the correlations are not significantly different from zero, we separated the data set into 11 groups of 50,000 records each, and calculated the correlations for each group. The scatter is sufficient that none of the correlations should be regarded as significant, with the possible exception of $L_{5,7}$. This correlation measures whether the communications personnel at a TCC and the mail delivery personnel at the base it services have comparable efficiency, so a moderate positive correlation is not unreasonable.

Because of the size of the data set, we could not analyze the outliers of the complete set as was done for the Flash set. However, the previous discussion of the end of the day, overnight, and weekend effects on the distributions serves the same purpose.

We fitted the curves for T_0, T_4, and T_I of Figs. 8 and 9 with broken-line lognormal distributions, and formed the compound distributions for the total ground delay, T_G, and entire delay, T_E, using

Eqs. (5) and (6) as before. The results are shown in Fig. 10. The percentiles of the total ground-delay distribution were included in Table 9 as the last column.

We see from Fig. 10 that the lognormal distribution provides a very good fit to the total ground delay T_G over the entire time range from one hour (0.01 percentile) to four days (83rd percentile). The transit time makes such a small contribution to the total delay that the curves can only be distinguished in the time range between one and two hours, through which the probability that the delay exceeds the abscissa drops from 99.99 percent to 99.9 percent. There is no particular point to plotting an enlarged version.

We conclude from Figs. 5 and 8 that for the AUTODIN I system, the transit delays only contribute significantly to the total delay when the total delay is less than two hours. For Flash messages, the contribution is at most a few percent. For the complete set, the transit delay is only discernible for the 0.1 percent of the total message set which have the shortest delays, and does not even affect them appreciably.

These conclusions apply to AUTODIN I as presently constituted. Our purpose in this report is to show how transit delays would be affected if millimeter waves were used for the communication portion of the message path, and also what would be the effect on the total delay. We have now established the delay distribution inherent in the existing system, and shall proceed to consider the millimeter-wave effects.

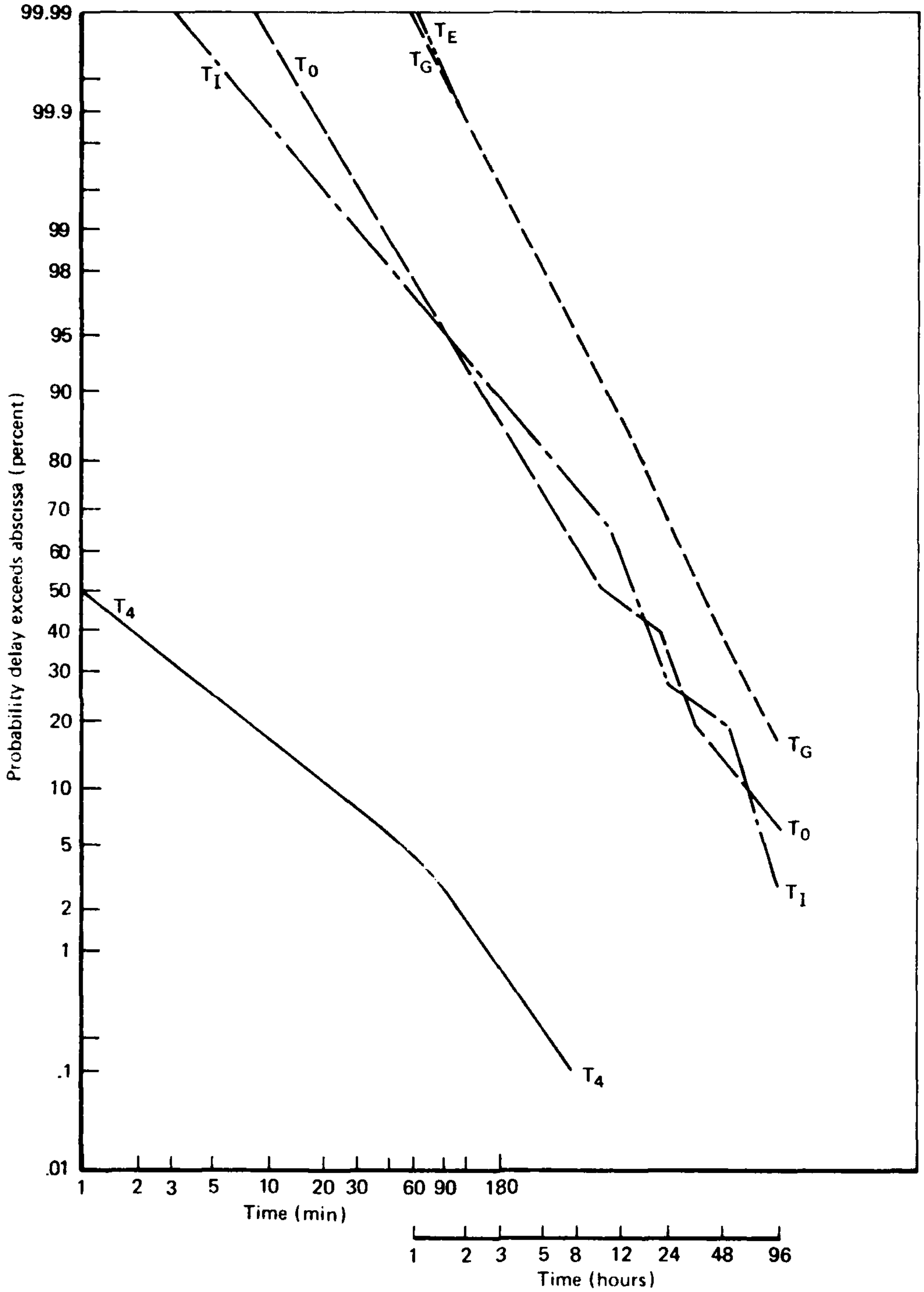

Fig. 10 — Probability distribution of combined handling times—all messages

III. DURATION OF RAIN-INDUCED OUTAGES

This section discusses the character and distribution of the duration of rain outages on millimeter-wave communication links. These rain-induced outages are an additional source of transit delay, and in Section IV they will be combined with existing transit and ground delays to ascertain the resulting effects on the complete communications system.

We first consider the rainfall intensity required to produce outages in millimeter-wave links between the earth and geosynchronous satellites. The rain rate required depends upon frequency, receiver characteristics, the elevation angle of the line of sight, geographical location, season of the year, and the margin allocated to rain-induced fades in the communications system. We shall average over certain of these parameters, and select others, to reduce the investigation to manageable size, eventually fixing on four values of rain rate which effectively span the relevant ranges of the several parameters.

Rain duration data used are relevant to the northeastern United States. After ascertaining for what fraction of the year the rain rate exceeds the indicated levels, we then use one-minute resolution data to determine the distribution of the duration of such rain intensities. This is the information needed to make comparisons with the AUTODIN data.

RAIN REQUIREMENTS TO PRODUCE OUTAGES

There have been investigations into the effects of rain on millimeter-wave communications systems for many years, and the literature is very extensive. Examples are the nearly 500-page January-June 1974 issue of the *Journal de Recherches Atmosphériques*, entirely devoted to rain properties and effects; the complete October 1979 issue of the *IEEE Transactions on Communications*, involving many problems of millimeter-wave communications; and survey articles by R. K. Crane[12] and S. H. Lin.[13] Most of the literature is devoted to either basic theory or measurements to establish the specific properties of rain attenuation, that is, at a given frequency how much attenuation is produced by a given rain rate. Other articles treat climatology and consider availability, that is, at a specified location and frequency, for what fraction of the total time does a millimeter-wave system experience outages. These articles are usually based on direct measurement of fading effects. Relatively few of the articles treat the duration of outages.

Direct measurement of fading in millimeter-wave systems (Refs. 13, 14, 15, and many other papers) provides important but limited information. They tell us what fraction of time a certain attenuation is produced, and may correlate the fading depth with rainfall intensity. What is required is a theory that assembles the various measurements and permits us to predict the attenuation as a function of basic quantities. Such a theory has been developed by R. K. Crane,[6,7] and we shall use it extensively in our analysis.

The first problem is to determine the rain intensity (we use the terms rain rate and rain intensity interchangeably) required to produce a fade of specified depth on an earth-satellite path. This rain rate will be a function of frequency and of the effective path length through the rain. The path length will depend on the elevation angle of the line of sight, the geographical location, and the season of the year. Furthermore, rain not only attenuates a signal, it produces excess noise in a receiver, and both effects must be considered. We shall assemble existing theories to treat this complicated situation.

We first consider the interaction of attenuation and noise production by rain. This phenomenon has been treated by many writers; we will follow the analysis of Ref. 2. The signal-to-noise ratio in a receiver is inversely proportional to the noise temperature and to the attenuation, regarded as a value, not a decibel number, greater than unity. If we divide the signal-to-noise ratio when it is raining by the ratio when it is dry, we eliminate the dependence on the power, antenna gain, and other internal parameters, and are left with the net signal reduction

$$A = \frac{T_D}{LT_R} \qquad (7)$$

where T_D is the noise temperature under dry conditions, T_R is the noise temperature when it is raining, and L is the attenuation caused by the rain. There should be no confusion between the letter T used here to denote temperature and the T used in other parts of this report to denote time. According to Ref. 2, pp. 21-22, the noise temperature under wet (dry) conditions is given by:

$$T = .89T_{SKY} + T_F + 56.3°K \tag{8}$$

where the first term is the "reduced" wet (dry) sky noise as viewed through the attenuating line and coupler, the second term is the front-end noise, and the additive constant is the sidelobe, line, and coupler noise. The front-end noise depends on frequency and on the particular devices used in the receiver. The sky noise depends on the rain intensity according to the relation:

$$T_{SKY} = T_a \left(1 - \frac{1}{L}\right) \tag{9}$$

where T_a, the sky background noise, varies slowly with frequency. Under dry conditions, assuming we are not near the oxygen absorption band at 55-65 GHz, L = 1 and T_{SKY} is zero. We combine Eqs. 7, 8, and 9, and solve for L, the attenuation, in terms of A, the total signal reduction, or fade depth, obtaining:

$$L = \frac{A + \dfrac{.89T_a}{T_F + 56.3}}{1 + \dfrac{.89T_a}{T_F + 56.3}} \tag{10}$$

This relation is to be applied to the downlinks (20 and 40 GHz) only. Because the satellite receiver on the uplinks observes the whole earth, its noise temperature is independent of the rain conditions at a particular transmission point. Therefore, for the uplinks (30 and 44 GHz), we set L = A. According to Ref. 2, p. 9, the sky background temperature T_a is about 275°K at 20 GHz, and about 265°K at 40 GHz. To determine the front-end noise T_F, we assume that any millimeter-wave system which might be coupled to AUTODIN would use the latest advances in technology. From Ref. 2, pp. 22-23, we select the cooled paramp as the front-end device, which could provide a front-end temperature of 17°K at 20 GHz and 22°K at 40 GHz. Combining the numbers, we obtain:

$$\frac{.89T_a}{T_F + 56.3} = \begin{matrix} 3.34 \text{ (20 GHz)} \\ 3.01 \text{ (40 GHz)} \end{matrix} \tag{11}$$

These values are to be used in Eq. (10).

We can now evaluate the attenuation L in terms of the effective fade depth A. We call on the Crane theory to express the attenuation L in terms of the rain rate R. This relation can then be inverted, yielding the rain rate required to produce a fade of specified depth A. From the Crane theory,[6,7] we have:

$$L(\text{dB}) = \alpha(f)\gamma(D)R^{\beta(f)-\delta(D)}H \csc \varepsilon \tag{12}$$

Here $\alpha(f)$ and $\beta(f)$ are functions of frequency. The elevation angle of the line of sight is ε, H is the height in kilometers of the atmospheric melting layer (0° isotherm), and $D = H \cot \varepsilon$ is the path length through the storm. The function $\gamma(D)$ measures the average inhomogeneity of the rain along the path, and $\delta(D)$, which involves the drop-size distribution, relates the inhomogeneity and the rain intensity. The rain rate R is measured in millimeters per hour. Curves for α, β, γ, and δ are given in Ref. 7. We list the values of α and β for the four frequencies under consideration in Table 11. These values measure the specific attenuation in dB/km.

We fitted the functions $\gamma(D)$ and $\delta(D)$ by simple mathematical functions that match the curves to better than 1 percent, which is more accurate than the curves themselves. The expressions are

$$\gamma(D) = [1 + .3864D + .0024D^2]/(1 + .12D) \tag{13a}$$

$$\delta(D) = .0525D(1 + .0172D)/(1 + .1063D) \tag{13b}$$

Table 11

PARAMETERS FOR SPECIFIC ATTENUATION

Frequency (GHz)	$\alpha(f)$	$\beta(f)$
20	.063	1.11
30	.165	1.08
40	.30	1.04
44	.38	1.02

which hold over the range 0 to 25 km for D, the relevant range for the theory.

Reference 7 gives a set of curves which plot the height of the melting layer versus latitude. The theory divides the world into a set of eight climate zones. Four of these are tropical or subtropical, and the height as presented does not depend on the season. The other four are temperate or polar, and curves are given for winter, spring-fall, and summer, averaged over the several zones. We do not regard this as a satisfactory description, especially since it shows the height of the layer as zero in winter, north of 45° latitude, implying that all precipitation falls as snow. Anyone who has experienced winter rains in the northern United States or western Europe knows better. We have gone to a primary source,[16] which plots isotherm height versus latitude on a monthly basis in 10° longitude steps around the world.

The ideal procedure for finding the effect of the use of millimeter waves on the delays in the AUTODIN I system would be to take each station, weight it according to the traffic it carries, and use rain information appropriate to the site. This is not practical for the following reasons. First, we only have traffic data for the first month of the study,[4] for which only 10 of the 13 stations were included. Second, we do not have rain information, either total occurrence or duration, for the specific locations of the ACCWRS investigation. Finally, the volume of calculation and results would be prohibitive. Clearly a simpler process is required.

Of the 13 stations in the ACCWRS investigation, six are in the eastern United States, two in the western United States (Denver and

Ft. Huachuca), one is in Hawaii, two in Germany, and two in Korea. In the eastern United States and in Germany, rain falls fairly evenly around the year, with a slight concentration during the summer. In Denver, the rain is scant (14 inches per year), and falls mostly in the late spring. In Fort Huachuca, the total rainfall is not enough to be significant. In Korea, the rain is heavy, with more than 75 percent falling between May and September. The base in Hawaii (Fort Shafter) is near Honolulu, where the rain is moderate and mainly in the winter. Korea and Denver have much less traffic than the other bases.

If we neglect the Korea and Denver traffic, and omit Ft. Huachuca because it is unaffected by rain, we have the eastern United States, Germany, and Hawaii. At Honolulu, the mean 0° isotherm is higher than in the other locations, but the total rainfall is considerably less, so we regard the outage time as comparable. In Germany, the mean 0° isotherm is lower and the total rainfall is lower, but the elevation angle must also be lower if we are to maintain a geosynchronous satellite link with the eastern United States. We consider the German stations also comparable with the eastern United States. If we take the eastern U.S. stations and average the storm heights over the seasons, weighting the seasonal contributions by the fraction of the annual rainfall which falls during that season, we obtain weighted annual averages for H which lie between 3.0 and 3.4 km (H ranges from about 1.5 to 2.2 km in winter, and about 4 to 4.5 km in summer). If we weight each station by its percent of the traffic, the mean value of H is 3.16 km. Data on isotherm heights for this derivation were obtained from Ref. 16, and data on worldwide monthly rainfall from the *Weather Handbook*.(17) We use the mean storm height 3.16 km as a fixed value to represent all stations.

The remaining parameter is elevation angle. As mentioned in the Introduction, we wish to treat worst-case situations, to avoid placing millimeter waves in an improperly favorable light. The U.S. stations of the ACCWRS analysis have latitudes ranging from 33°N to 40°N, the German stations are near 49°N, the Korean stations near 37°N, and Hawaii at 21°N. For Hawaii or Korea to communicate with the continental United States via a synchronous equatorial satellite, using a receiving station in Los Angeles, and the most favorable location for the satellite (128°W for Honolulu-Los Angeles, 175°W for Seoul-Los Angeles), the elevation angles are about 49° and 17°, respectively. For the eastern U.S. stations to communicate with each other via a satellite at 80°W, the elevation angles range from about 34° to 40°. The present AUTODIN system has transatlantic communications stations at Andrews AFB near Washington, D.C., at Croughton, England, and at Pirmasens, West Germany. From Andrews, the elevation angle range 20° to 30° is subtended at synchronous altitude by the equatorial section 14.2°W to 38.6°W, from Pirmasens the same elevation angle range is subtended by the equatorial section 36.1°W to 24.4°W, which is common with Andrews. It is most likely that if millimeter-wave satellite links were to be employed for any portion of a U.S. military communications system, they would be used on a transoceanic section, for which the fewest number of redundant systems would generally be available. If we choose the elevation angle range 20° to 30°, and in particular its endpoints, we see that we have made a choice which is as unfavorable to millimeter waves as is reasonable (only the Korea-U.S. link, with low traffic, is lower, and it only slightly). We therefore select 20° and 30° as the elevation angles to be considered.

With these choices of parameters, we can now invert Eq. (12) and determine the rain rate required to produce a specified fade depth (A) for the various link conditions. The storm height has been fixed at 3.16 km and the elevation angles at 20° and 30°. The four frequencies 20, 30, 40, and 44 GHz are treated, with fade depths of 5, 10, 15, and 20 dB, which should cover all reasonable values of system margin. (A system with only 5 dB of fade margin is overly sensitive, one with more than 20 dB of fade margin is probably, although not assuredly, overdesigned.) The results are presented in Table 12.

We choose from this array values which will represent the range required: 1, 3, 7, and 20 mm/hr. The worst conditions in Table 12 (highest frequencies, lowest angles, poorest fade margins) are represented by 1 mm/hr. The next, 3 mm/hr, covers high frequencies at either low angles and better margins or higher angles at poor margins, and low frequencies at low angles and poor margins. The 7 mm/hr rain rate

Table 12

RAIN RATE REQUIRED FOR SPECIFIED FADE DEPTH

Elevation Angle = 20°

Fade Level, dB	Frequency, GHz			
	20 (Down)	30 (Up)	40 (Down)	44 (Up)
	Rain Rate Required (mm/hr)			
5	1.4	1.6	.2	.6
10	4.9	3.8	.8	1.4
15	10.2	6.3	1.7	2.4
20	16.8	14.9	2.9	3.5

Elevation Angle = 30°

Fade Level, dB	Frequency, GHz			
	20 (Down)	30 (Up)	40 (Down)	44 (Up)
	Rain Rate Required (mm/hr)			
5	2.5	2.8	.5	1.1
10	7.7	6.2	1.5	2.6
15	15.1	9.8	3.1	4.2
20	23.9	13.6	5.0	6.0

corresponds to high frequencies at higher angles and good margins, or low frequencies at higher angles and poor margins, and the 20 mm/hr rate to the best conditions (low frequencies, good margins).

We have now reduced the rain rate requirements problem to a few numbers. The temporal distribution of such rainfall is discussed next.

RAINFALL DURATION DISTRIBUTIONS

Now that outage-producing rainfall intensities have been established, we ask, how long does such rain last? First, what fraction of the total rain per year, or other long-term average, falls at rates exceeding the indicated levels? We would normally use the curves of rain intensity distribution for the Crane theory, since we are accepting the other aspects of this theory. However, at rain intensities of 20 mm or below these curves are unreadable (see Fig. 1 of Ref. 7), and other sources must be consulted.

Rain data is needed for the eastern United States, particularly in the Washington, D.C., area, since that is where the AUTODIN satellite terminal is located. Measurements of annual average rainfall intensities have been collected at many places in the eastern United States, and there are dozens of references. Examples are data from Montreal,[18] New Jersey,[13,19] North Carolina,[14,19] Atlanta,[20] and Miami.[19,20] In a long series of papers, which culminate in Ref. 13, S. H. Lin has demonstrated that the rain rate intensity distribution is lognormal. Unfortunately, most of the data were collected at high rain rates with the intent of applying it to communications satellites in the 11 to 17 GHz band, and data are lacking at the rain levels of interest here.

We selected as the most appropriate data measurements by the Illinois State Water Survey at Island Beach, New Jersey.[19] These measurements cover the year from May 1961 to May 1962. The data range extends from 0.25 mm/hr to 190 mm/hr, presented in equal steps in the logarithm of the rain rate, with a total of 30 steps covering the range. The measurements, obtained by a weighing-bucket rain gauge, are listed as mean monthly values plus the annual average, and the entries are nominally three significant figures. These data are much superior to the other measurements in coverage and resolution.

Island Beach is located on the New Jersey coast, about 175 miles northeast of Washington, D.C. There are no intervening mountains. We can expect the Island Beach climate to be quite similar to the Washington climate, since the month by month rainfall in Atlantic City, N.J., (40 miles from Island Beach) matches that in Washington[17] to within the accuracy of the measurements. Furthermore, we obtained measurements of the rain at Island Beach with a time resolution of one minute, and thus can make the comparisons with AUTODIN delays. The Island Beach measurements will be used to represent the rainfall statistics for the entire system.

Is this representation reasonable? Island Beach can certainly represent Washington. At the more southerly stations, a greater percentage of the rainfall is of convective character, and hence the higher rain rates occur more frequently. However, this increase in rain at higher intensities is partially compensated by a reduction in the time during which it is raining lightly. In fact, if we compare the total time it is raining in Miami[19] with the total time it is raining at Island Beach (minimum intensity level 0.25 mm/hr = 0.01 in./hr, the limiting resolution), we find 2.57 percent for Miami and 4.33 percent for Island Beach. Hence, the use of the Island Beach data for all locations overestimates the low intensity levels and underestimates the high levels. If all the overseas traffic is funneled through a station near Washington, these results should be reasonably accurate. We accept this situation.

The fraction of the year that the rain intensity at Island Beach exceeds the indicated levels is presented in Table 13.

Table 13

ANNUAL OCCURRENCE OF RAIN INTENSITIES,
ISLAND BEACH, NEW JERSEY

Rain Rate, mm/hr	Occurrence	
	% of Year	Hours/Year
1	3.0	263
3	1.1	96
7	.26	22.8
20	.054	4.7

Those figures give us the annual availability, which is where most previous studies stopped. We next consider the high-resolution temporal distribution of these rain events.

DISTRIBUTION OF OUTAGE DURATIONS

Not nearly as much data on rain rates have been collected at high time resolution as have been assembled for annual averages, and most of the data are at high rain intensities. Direct measurements of fade duration have been assembled in a fairly early paper by Lin,[21] and he gives more recent measurements in Ref. 13. These measurements, mostly from Georgia and New Jersey, give quite excellent lognormal fits, but they are expressed in terms of so many dB fade on a given path and are difficult to generalize. Measurements in Montreal[18] display lognormal duration distributions, but do not correlate duration and intensity. Measurements in Japan[22] indicate a reciprocal relation between the rain rate and its mean duration, but are hard to interpret. Measurements in Paris[23] indicate a beautiful lognormal relationship, but only provide data at 100 mm/hr and 15 mm/hr, with no way to obtain further information.

Another study by the Illinois State Water Survey[24] provided duration data at good time resolution for several locations, including Island Beach, but the only low rate included was 12 mm/hr. We communicated with Dr. Richard E. Semonin, who now heads the Illinois group, to ascertain whether they still had the original data from which the duration distribution of Ref. 24 was produced, and offered to reduce the data ourselves. Dr. Semonin, without whose cooperation our research could not have been satisfactorily completed, sought without success to find the original tapes. However, he referred us to another Illinois State Water Survey project, not published under their name, which used a drop camera to measure drop-size distributions.[25] In the course of such measurements, they determined the rain intensity as a function of time with one-minute resolution. The unreduced data were published in a series of reports, which we secured.

The technique of Ref. 25, which was conducted at Island Beach and six other locations, is worth describing. An optical system sampled rainfall by taking photographs of the raindrops falling through a specific volume--a right circular cylinder approximately 29 inches in diameter and 14 inches deep, with an unobstructed volume of about 1/7 cubic meter. Each minute, seven photographs were taken in a 10.5 second period. The film was projected onto a translucent screen, so the drop images were twice their actual size. The major and minor axes were measured and used to calculate the equivalent spherical diameter, and the diameters tabulated into a size-frequency distribution for each one-minute sample. Several parameters were calculated from this distribution, among them the rain rate, calculated from the equation:

$$R = K \int_0^{\infty} N(D) D^3 v(D) dD \tag{14}$$

where D is the drop diameter,* $N(D)dD$ is the number of drops in the size interval D to D + dD, $v(D)$ is the terminal fall velocity for a drop of size D,[26] and K is a constant to adjust units. The date, time in one-minute intervals, rain rate, other parameters, and the drop-size distribution are tabulated for a total of 3135 samples, obtained during the period October 30, 1960 to May 24, 1962. The rain rate is given to an indicated accuracy of 0.1 mm/hr, with a least value 0.2 mm/hr and a greatest value of 155 mm/hr on August 11, 1961.

What we desire for our comparison with the AUTODIN data are rain duration data with about the same time resolution as the AUTODIN data, that is, one minute. The data of Ref. 25 provide such resolution. However, there is a question concerning the meaning of the averaging over seven pictures, 1.5 seconds apart, to obtain the one-minute data. A very extensive investigation by the Bell Laboratories[27] has shown that intense rainfall is very spiky in its temporal character, with one-second swings up to 150 mm/hr when the ten-second average is 50 mm/hr. However, we do not anticipate that this effect will be significant at the much lower rain rates with which we are concerned in this report, and we use the nominal one-minute resolution of Ref. 25 as the actual time resolution.

The data of Ref. 25 were reduced by hand and eye. For each of the four selected rain intensities (1, 3, 7, and 20 mm/hr), we read down the time and rain rate columns and recorded the starting and ending time of each episode of rain exceeding the indicated level. If there were two episodes very close together in time, with one or two minutes

*Do not confuse with the path length D of the Crane theory.

separating them, during which the rain falls slightly (0.1 mm/hr for the 1 mm/hr data, 0.2 mm/hr for the other levels) below the scanning level, we counted them as a single episode. The resulting duration data were put into bins and the cumulative distribution obtained. The results are shown in Fig. 11. The lognormal character of the distributions is evident. The distributions for 7 and 20 mm/hr are not distinguishable for durations less than four minutes. Because of the one-minute resolution, the values at 1 and 2 minutes should not be regarded as reliable.

We list in Table 14 some properties of the distributions of Fig. 11. Included are the number of episodes at each level, the median and mean durations, and the longest episode observed.

The annual average data of Table 13 and the high-resolution data of Table 14 were taken at the same location during the same overall time period. However, the rain gauge data of Table 13 measured all the rain in the period, whereas the camera system of Table 14 only collected data when there was film in the camera and it was properly triggered. Hence, the total data sample of Table 14 is smaller than that of Table 13. Nevertheless, the number of episodes is sufficiently large that we shall regard Fig. 11 and Table 14 as proper representations of the complete measurements in Table 13, and scale the distributions of Fig. 11 by the total occurrence time of Table 13 to describe the distribution of rain-induced delays on an annual basis.

We see from Tables 13 and 14 that although the total outage time, as a percent of the year, may be quite large, it is composed of many short episodes. For example, if we divide the total outage time at a critical level of 3 mm/hr, 96 hr/year, by the mean outage duration 5.5 minutes, we expect about 1000 short outages per year, half of which will be shorter than 2.2 minutes, and only 5 percent of which will exceed 20 minutes. These are the types of delays which should be compared with the AUTODIN delays of Section II.

As discussed, we regard the Island Beach data as representative of the entire eastern United States, and now proceed to combine the rain delay distribution of Fig. 11 with the transit and total delay distributions of the AUTODIN system for Flash and overall message traffic.

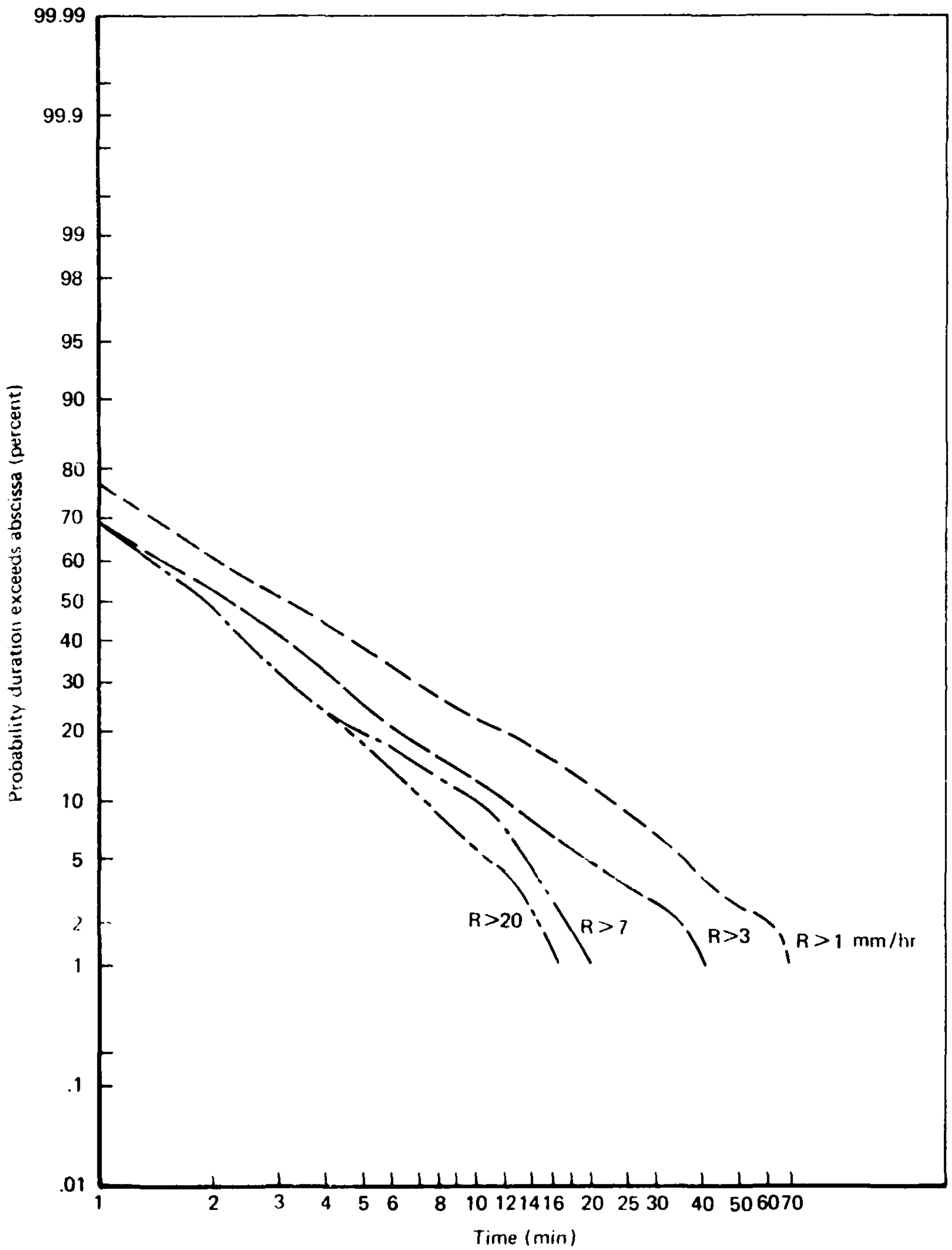

Fig. 11—Rainfall duration distributions, Island Beach, N.J.

Table 14

PARAMETERS OF THE RAINFALL DURATION DISTRIBUTIONS

Rain Rate, mm/hr	Number of Episodes	Median Duration, min	Mean Duration, min	Longest Duration, min
1	268	3.2	8.7	75
3	213	2.2	5.5	50
7	111	2.0	4.0	26
20	29	2.0	3.8	22

IV. COMBINED RAIN AND AUTODIN DELAY DISTRIBUTIONS

METHOD OF COMBINATION

Recapitulating, we have studied in considerable detail in Section II the delay distributions in the AUTODIN system. Figure 5 displays for Flash traffic the probability distributions for outgoing, transit, and incoming delays, the total ground delay, and the grand total delay. Figure 10 provides the same information for the complete message set. We established in Section III the rain rate required to produce an outage in a millimeter-wave link under a broad range of conditions, and the distribution of the duration of such rain rates is shown in Fig. 11. We must now consider how to combine the several delays to determine the effect of the use of millimeter-wave communication links on a military communications system such as AUTODIN.

When we combined the outgoing and incoming distributions to form the total ground-delay distribution, and then convolved it with the transit-delay distribution to obtain the complete distribution, we used the fact that the delays are sequential, so the total delay is the non-overlapping sum of its parts. However, the rain-induced delay is an independent source, and we must consider the relation between the starting time of the message in transit and the starting time of the rain.

The transit delay in the absence of rain involves a queueing delay, in which the message waits at the outgoing ASC for its turn to be transmitted, plus the physical time of transmission, which is about 1/4 second for a message to travel to a geosynchronous satellite and back, plus a time, the product of the circuit speed per character and the number of characters, which is the time the message takes to traverse the circuit, plus a possible queue at the receiving ASC. A rain outage can start at any phase in this cycle, and can be on either the up or down link (an outage on both up and down links simultaneously is very rare). Uplink outages can be anticipated by the transmitting ASC, who might observe the beginning of rain sufficient to cause an outage, and shut down his transmitter, thereby avoiding the possible loss of messages. If an outage occurs on the down link, the transmitting ASC would not be aware of the loss of signal until he failed to receive the automatic acknowledgment from the receiving ASC.

If the transmitter shuts down at the beginning of the rain outage, holds the messages until the end, then begins transmitting again, the effect of the rain outage will be to add another sequential source of delay, which can be treated by convolution, as before. There will be an increase in the queueing delay for those messages which arrived during the rain interval, since the queue will be unable to discharge. Data from Ref. 4 indicate that the mean number of messages per day per station was near 200. Data from the 15 days for which we have the complete DCA records show that the average number of messages per day for the entire AUTODIN network was about 330,000. With 765 stations, this would yield an average per station of about 430. Some, of course, have more, some less, but the mean should be representative. Assuming these arrive at a uniform rate during an eight-hour period gives a mean message spacing of about 1-1/2 minutes, which is of the same order of magnitude as the median rain delay. Hence, the length of the queue should not be seriously extended. Also, extensive alternate routing schemes currently employed at AUTODIN will further tend to reduce the severity of rain outage queues.

Some messages may have been transmitted during the rain outage and not arrive at the receiver. These will be identified when they fail acknowledgment, and will be retransmitted after the outage ceases. They may leapfrog the queue, in which case they will be in the set of messages for which we can regard the delay as sequential. Otherwise, they will experience double the queueing delay. Since such messages should only occur during the onset of rain, their number should be small.

At the receiving ASC, the effect of a rain outage is to produce a gap in the flow of incoming data. The queue, if any, at the receiver will discharge, and the receiver will wait for the new incoming message. Thus, delays at the receiver are approximately sequential, with the queueing delays reduced, partially compensating the increase in queueing delay at the transmitter.

From these several considerations, we have decided to treat rain-induced outages as a sequential source of delay to be added to the transit delay to obtain the effective delay during rain periods. This is only an approximate description of a much more complicated situation, but we regard it as sufficiently accurate, and a more thorough treatment would require very extensive analysis, for which we lack the time, money, and inclination. Thus, we shall use the convolution process of Eq. (5) to incorporate the rain-induced outages into the complete delay distributions.

These combined distributions tell us what effects would be produced in the AUTODIN system if it used millimeter-wave links exclusively. The changes in the real system would, of course, be much less, since other communications media can be used. Thus, we are again employing a worst-case analysis.

COMBINED DELAYS FOR FLASH MESSAGES

Our first operation is to convolve the distribution of the transit delay, T_4, for Flash messages, shown in Fig. 4, and the rain-delay distributions of Fig. 11, regarding the delays as sequential and using Eq. (5) for the combination. The curves of Fig. 11 are fitted with broken-line lognormal distributions, which from the appearance of Fig. 11 will be very accurate. The results are shown in Fig. 12, covering the first two hours of the delay distribution, which includes essentially all the messages. The curve for $R > 20$ is not shown; it lies slightly below the $R > 7$ curve.

The labels on Fig. 12 are to be interpreted as follows. The curve labeled Dry is the present AUTODIN transit delay curve for Flash messages, an expanded scale version of the T_4 curve of Fig. 5. It corresponds to conditions for which an infinite (or at least very large) rain intensity is required to produce an outage. The curve labeled $R > 7$ is the convolution of the Dry curve and the $R > 7$ curve of Fig. 11. It represents the delay which a system with the Dry characteristics would experience if a rain intensity greater than 7 mm/hr would cause an outage. The curves $R > 3$ and $R > 1$ are similar. These curves apply to the distribution of transit delays during the periods when it is raining. If it is not raining, or is raining at a rate less than the critical level, the Dry curve applies to system delays.

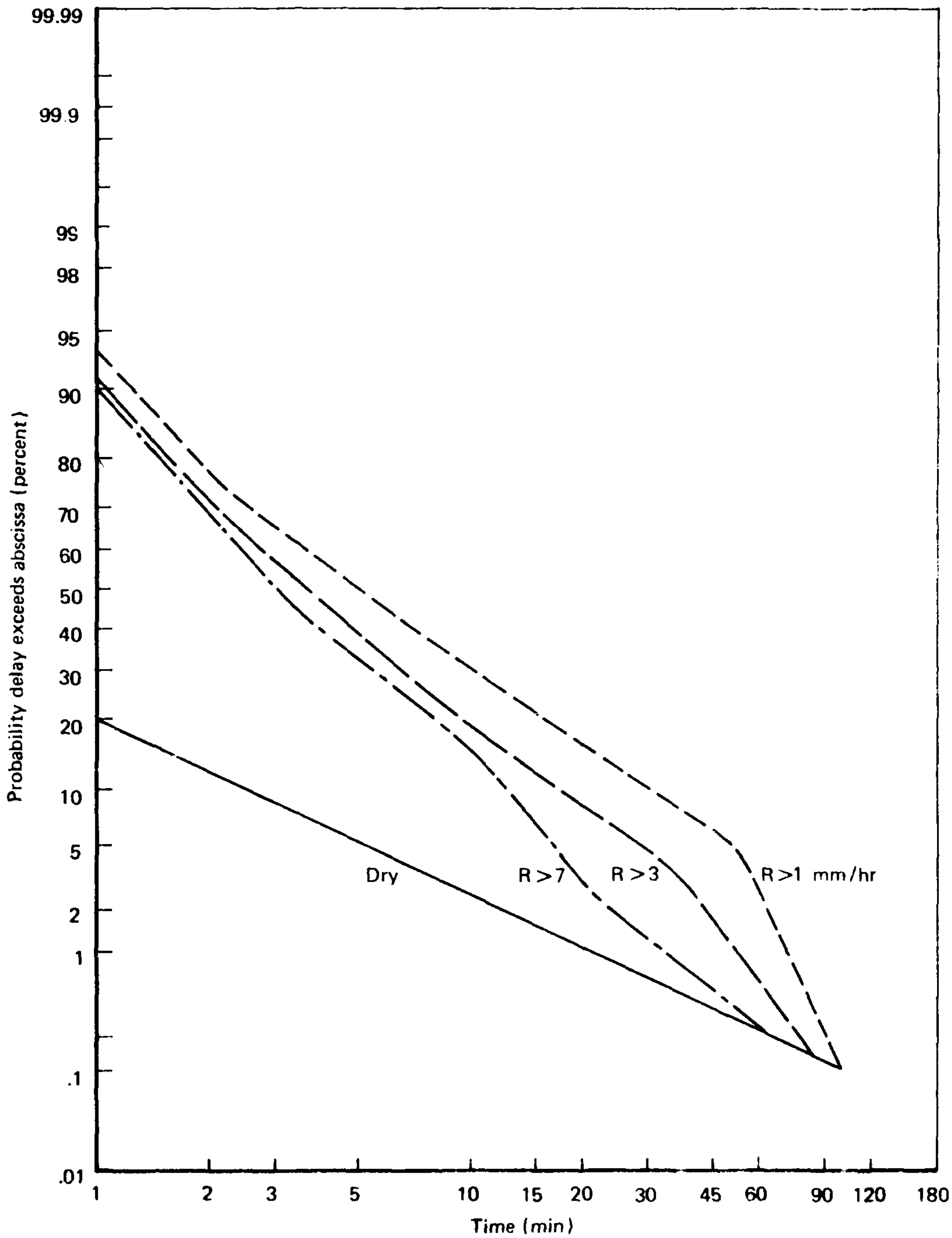

Fig. 12—Transit delays during rain periods – Flash messages

Figure 12 displays the dreaded effect of rain outages on transit delays. If we examine the worst case, $R > 1$, corresponding to a 40 to 44 GHz system in the Washington, D.C., area with an elevation angle of 20° and a fade margin of 10 dB, we see that in dry periods, the system passes 90 percent of the messages in about 2.5 minutes, and 98 percent of the messages in 12 minutes, whereas during rainy periods it passes only 30 percent of the messages in 2.5 minutes, and 75 percent in 12 minutes. It takes 30 minutes to reach the 90 percent mark, and 62 minutes for 98 percent. If we look at the median level, the delay in dry periods is below one minute (about 0.2 min if the line of Fig. 12 is extrapolated leftward), but is about five minutes during time intervals which include rain episodes with intensity greater than 1 mm/hr, or three minutes for rain intensity greater than 7 mm/hr.

These are real and significant effects. If it rained most of the time, or if transit delay were the only source of delays in the communications system, they would probably justify a decision to not employ millimeter waves in a military communications system devoted to transmitting Flash messages. However, a millimeter-wave station would not be placed on Mt. Waialeale, Kauai, Hawaii (annual rainfall 460 inches/year), or in a tropical rain forest. Rather, it is expected that ground stations for millimeter-wave satellite links would be placed in locations chosen so that it rains a comparatively small fraction of the year (see Table 13). It was shown in Section II that the ground delays are large compared with the transit delays. For the AUTODIN system, Flash traffic constitutes only about 0.15 percent of the total message traffic of the ACCWRS analysis, or about 0.05 percent of the total message traffic of the 15 DCA daily records. The proper perspective for Fig. 12 is obtained by taking these other effects into account.

We first consider the fact that it only rains a small fraction of the time. According to Table 12, a rain rate exceeding 1 mm/hr occurs about 3 percent of the year at Island Beach. Thus, we obtain a measure of the effective delay distribution for a system using millimeter waves by forming the weighted sum of the Dry curve with a weight of 97 percent and the $R > 1$ curve with a weight of 3 percent. This combination represents the Flash transit delay viewed on an annual average basis. For a heavy traffic system such as AUTODIN, this is a more reasonable picture of the effect of millimeter waves than is concentration on the delay distribution during rain periods portrayed in Fig. 12. The result is shown in Fig. 13, where only the Dry and weighted R > 1 distributions are shown. The distributions for the other rain levels lie between the curves, much closer to the Dry distribution, since the weights for the rain intervals are less.

We see from Fig. 13 that on an annual average basis, the transit-delay distribution for the system employing millimeter waves is not significantly different from the system which does not employ them. At the 10 percent level, the change in delay is from about 2.5 minutes without millimeter waves to about 3.2 minutes; at the 2 percent level, from about 12 to 15 minutes. These changes measure the net annual average effect on the delay distribution for Flash messages that would be produced by employing millimeter waves in a communication system whose transmission characteristics were the same as AUTODIN, but for which all other sources of delay had been magically eliminated. We regard the changes as slight. Not negligible, but slight.

We next consider the interaction between rain-modified transit delays and other sources of delay. This is treated by forming the convolution between the curve labeled T_G in Fig. 5, which represents the total delay produced by ground processes, and the rain-delay distribution curves of Fig. 12. The results are shown in Fig. 14. The curve marked Dry in Fig. 14 is identical with the curve T_E in Fig. 12, and describes the total delay distribution for the AUTODIN system as is. The curve labeled R > 1 shows the total delay for our worst-case system employing millimeter waves, and the unidentified curves in between are for R > 3 (right) and R > 7 (left).

As expected, the effects of rain on the delay distribution, including ground delays, are considerably less than the effect on transit delays. The Dry system takes 25 minutes to handle 10 percent of the Flash messages, 45 minutes to handle 30 percent, and 100 minutes for half the messages. The system whose communications links are put out of action by a rain intensity greater than 1 mm/hr takes 31 minutes for 10 percent of the messages, 53 minutes for 30 percent, and 108 minutes

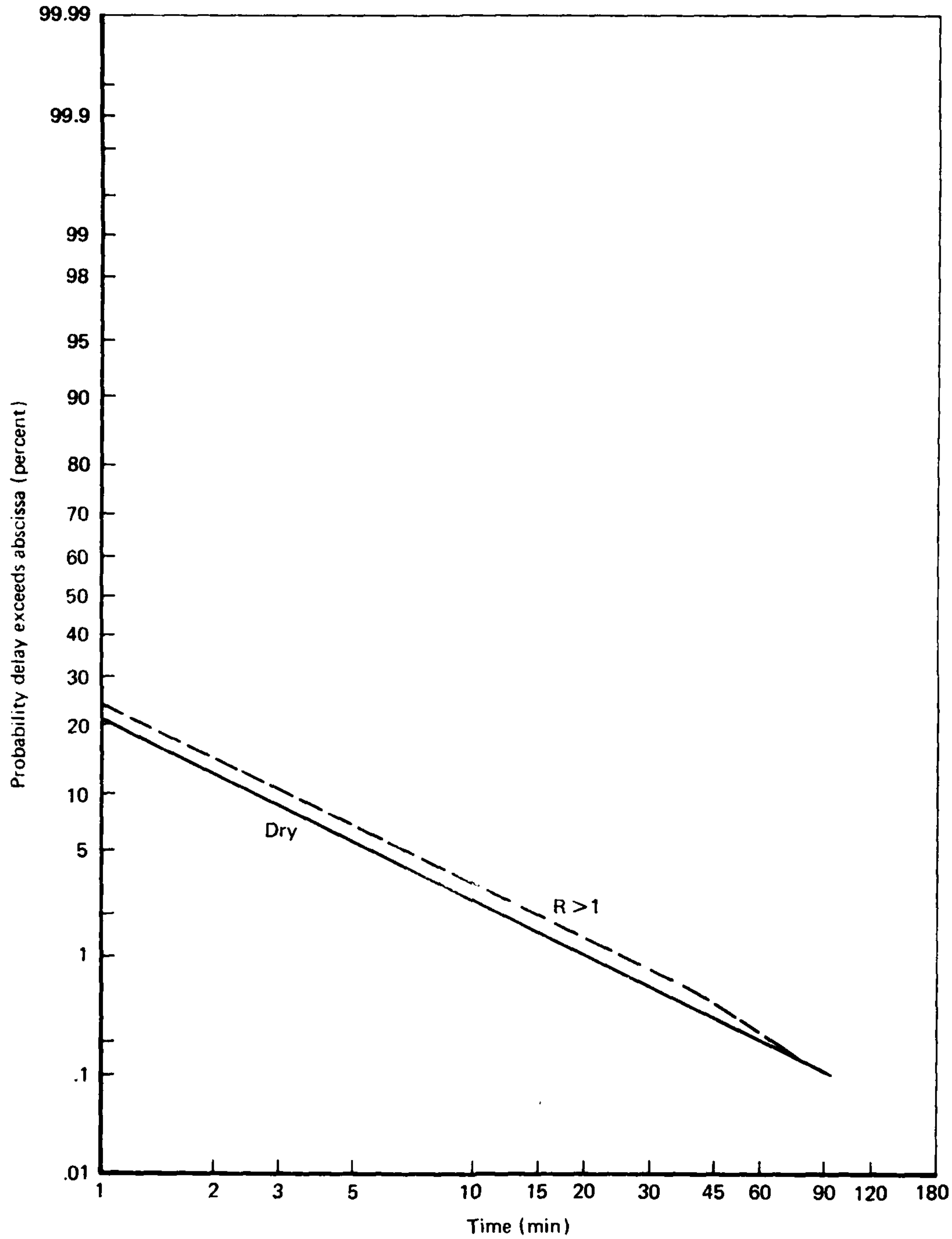

Fig. 13 — Annual average transit delays — Flash messages

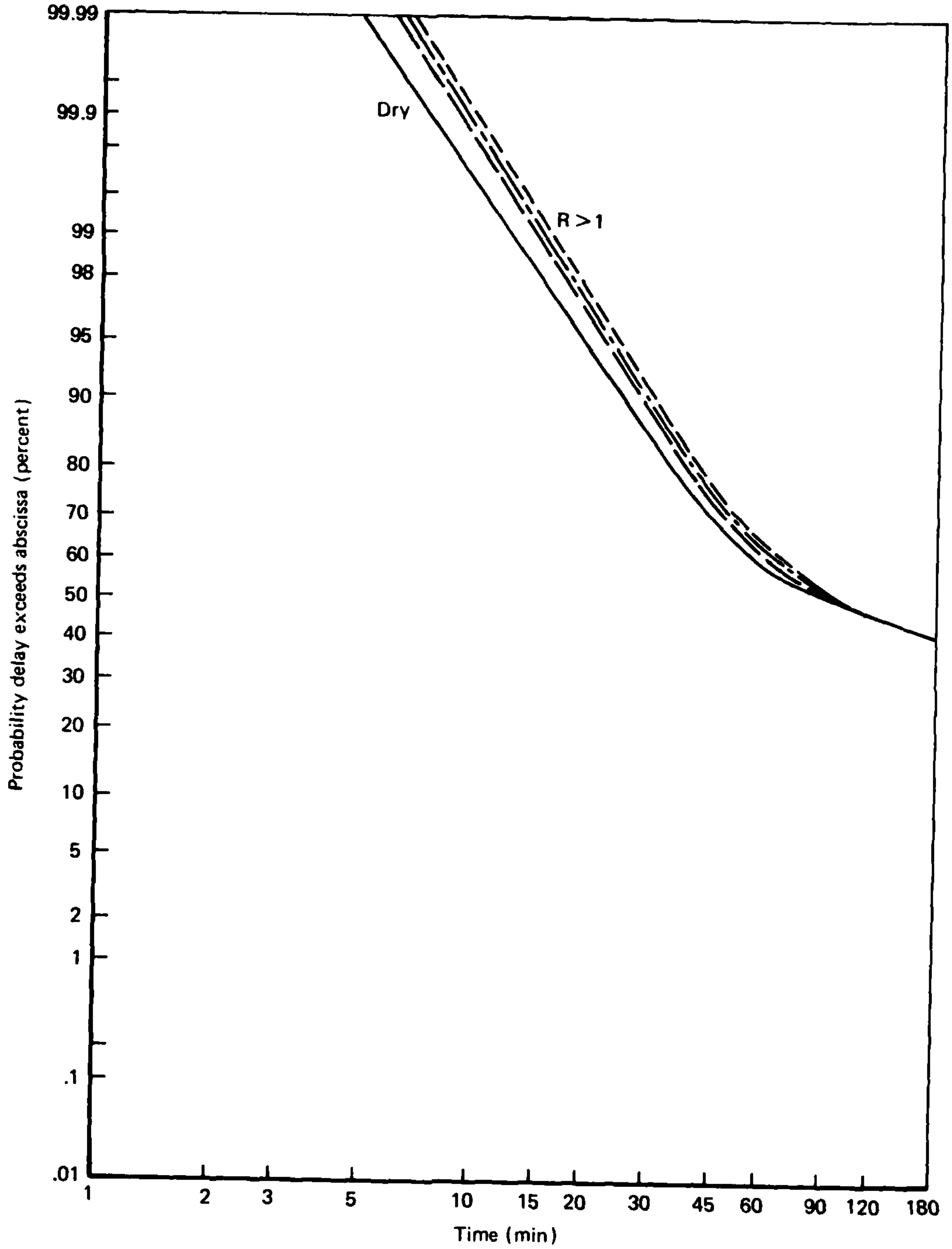

Fig. 14—Total delays during rain periods—Flash messages

for half the messages. Beyond the 50 percent level, the curves cannot be distinguished on the logarithmic time scale. These changes are relatively much smaller than the changes in transit delay, and show that even during rain periods the ground delays are so much larger than the rain-affected transit delays that the change, while noticeable, is not very important.

Our last comparison is for the annual average total delay. This is obtained by weighting the Dry curve of Fig. 14 by 97 percent, the $R > 1$ curve by 3 percent, and adding. The Dry and $R > 1$ curves are shown in Fig. 15. Contrary to appearances, there are two curves on the figure, but they can only be distinguished near 60 percent. We conclude from Fig. 15 that the effect of rain outages on the total system delay, averaging over wet and dry periods, is quite negligible.

This set of comparisons covers our treatment of the effect of rain outages on delays in the AUTODIN system for Flash messages. We next consider the effect on the complete message distribution.

COMBINED DELAYS FOR THE COMPLETE MESSAGE DISTRIBUTION

Figure 16, analogous to Fig. 12, shows the transit delays for the complete message distribution as affected by rain outages. The two figures are generally similar. There is less rain effect on the transit delay for the complete distribution than there was for the Flash distribution. This is because the transit delay for the complete message set in the absence of rain is significantly greater than for the Flash set, and hence the relative effect of the rain-induced delays will be less. The Dry system passes half the messages in one minute, 70 percent of them in 3.2 minutes, 90 percent in 21 minutes, and 98 percent in 97 minutes, whereas the system which experiences outages for $R > 1$ passes half the messages in 7.3 minutes, 70 percent of them in 16 minutes, 90 percent in 50 minutes, and 98 percent in 126 minutes. In Table 15 we compare this increase in delay with those for Flash messages.

We see from Table 15 that the absolute increases in transit delay are comparable for Flash messages and the complete set. The ratio, which is the quotient of the time required to transmit the indicated fraction of messages for the system with rain-induced outages and the

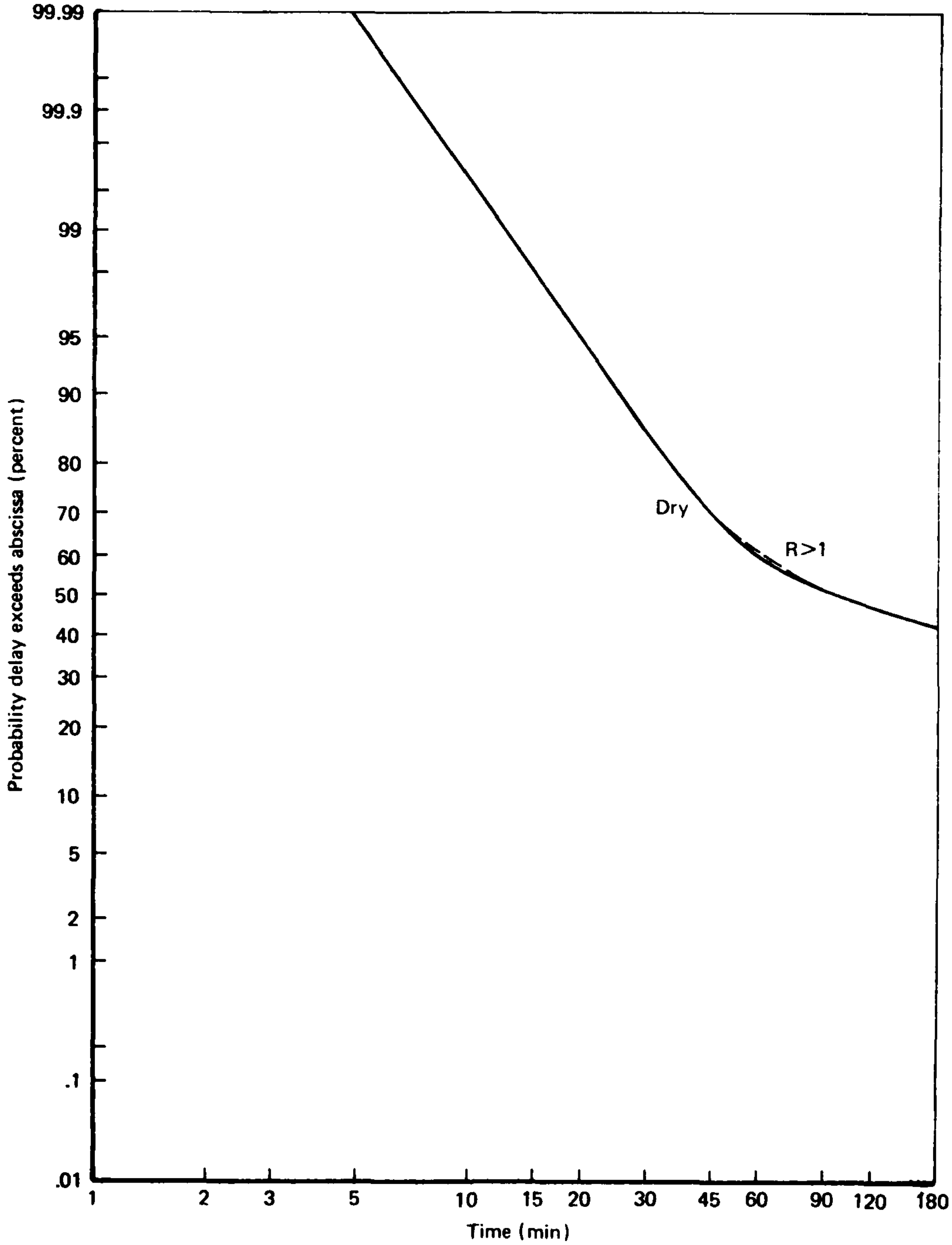

Fig. 15—Annual average total delays—Flash messages

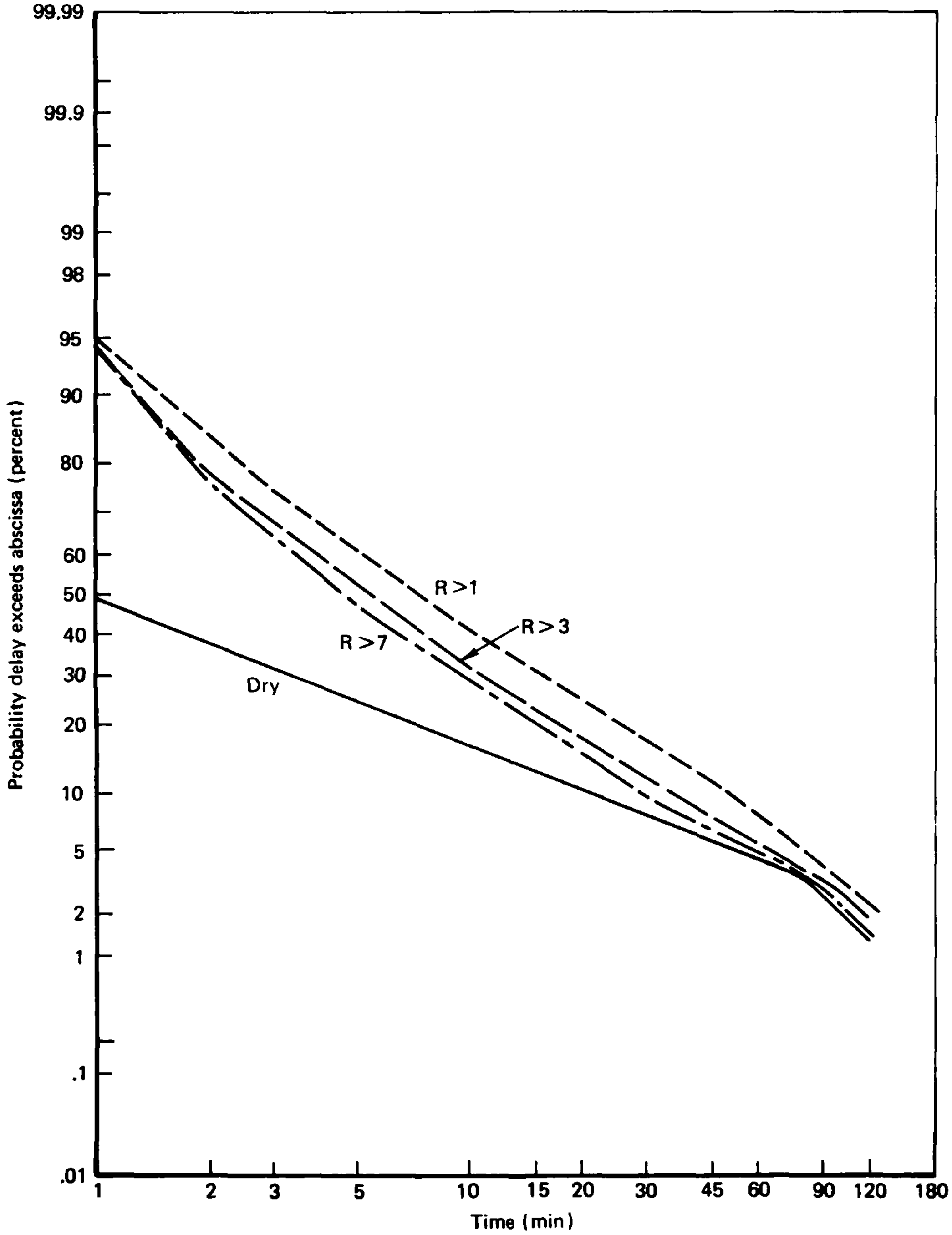

Fig. 16 — Transit delays during rain periods--all messages

Table 15

INCREASES IN TRANSIT DELAY

Percentile	Flash Messages		All Messages	
	Increase (Min)	Delay Ratio, Wet/Dry	Increase (Min)	Delay Ratio, Wet/Dry
50	4.8	25	6.3	7.3
30	10.4	16	12.8	5
10	27.5	12	29	2.4
2	50	5.2	29	1.3

corresponding time for the Dry system, is much larger for the Flash messages than for the complete set. The very large difference between the delay increase at the 2nd percentile for Flash messages and for the complete set (21 minutes) is caused by the fact that at this level, almost all of the delay for the Flash messages results from rain, whereas for the complete set the rain and the inherent delays in the system make nearly equal contributions.

From Fig. 16, we conclude that the rain-induced delays are real and significant compared with transit delays during rain periods for the complete message set. We again put this deduction into context by considering the annual average and the effect of ground delays.

We combine the Dry and $R > 1$ distributions with relative weights 97 percent and 3 percent, corresponding to the fraction of time it is raining in Island Beach, and show the results in Fig. 17. Evidently the difference between the curves is much smaller than in Fig. 13. It may be concluded that on an annual average basis, the effect of rain-induced outages on the transit delays of the complete message distribution is not significant.

Referring back to Fig. 10, it is seen that the ground delays for the complete message distribution are so much greater than the transit delays that the curves for T_G, the ground delay, and T_E, the total delay, can only be distinguished above the 99.9 percent probability level, which includes only 0.1 percent of the messages. If we combine ground delays and rain-affected transit delays, the change from pure ground

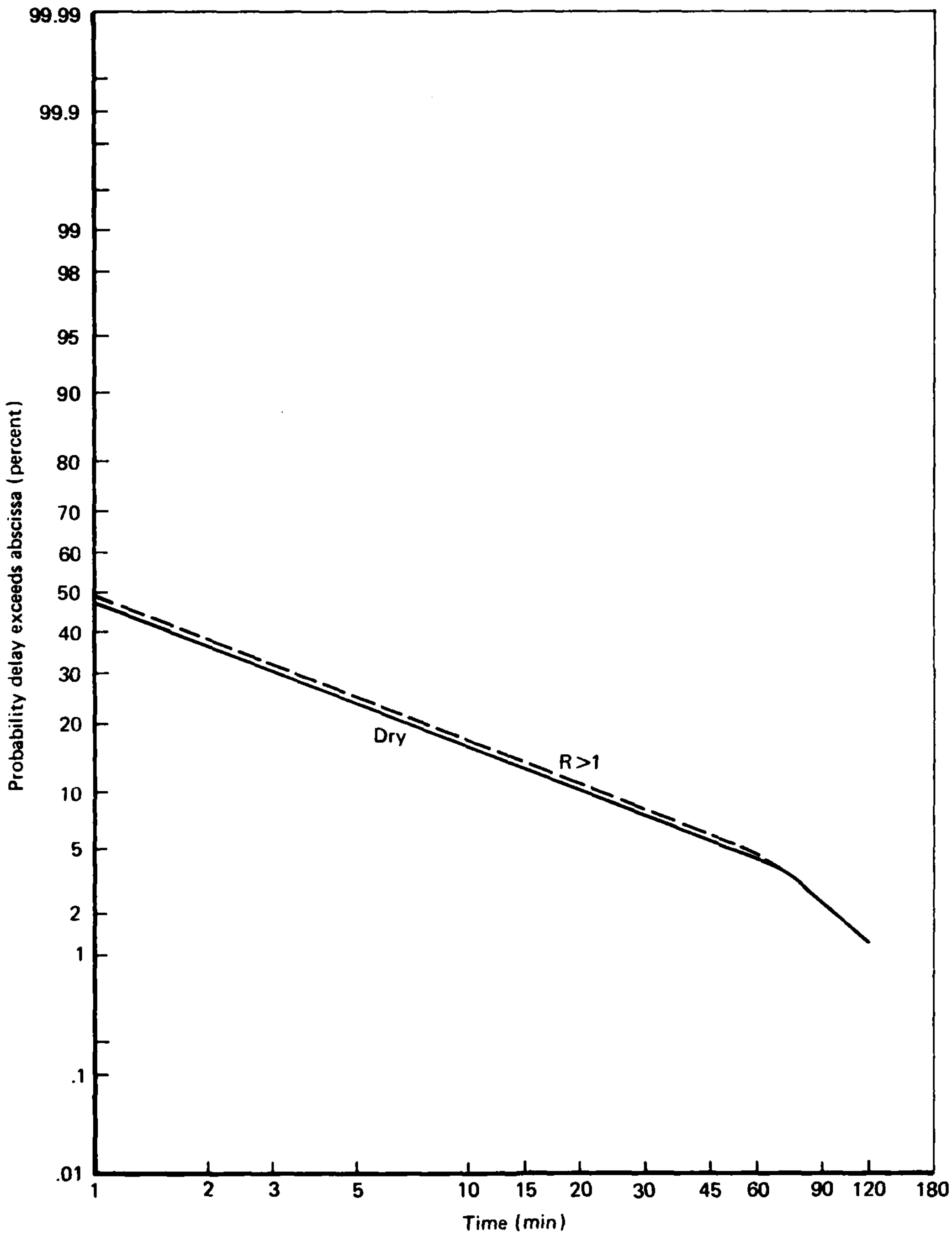

Fig. 17—Annual average transit delays—all messages

delay can only be shown on a greatly expanded scale. The curve will be displaced a few minutes to the right (five minutes at 99.99, 10 minutes at 99.9), and the effect of rain delays on all but the fastest 0.1 percent of the messages is quite insignificant during rain and absolutely negligible on an annual average basis.

OTHER CONSIDERATIONS

We have demonstrated in perhaps excessive detail that all the delay distributions encountered, both for the message sets and for the rain durations, are approximately piecewise lognormal. It is reasonable to ask why this condition should prevail. Just as a normal distribution may be formed by adding many variables, a lognormal distribution may be formed by multiplying many variables. Lin,[13] in his treatment of the lognormal character of rain attenuation levels, displayed a correlation between rain attenuation and its time derivative (his Fig. 29) from which he deduced that "the environmental parameters affect the rain attenuation in a proportional fashion." He also observed the lognormal distribution of fade duration, but could not make a comparable deduction. We do not see what properties of rain could combine multiplicatively to determine its duration, and we also do not see how message delay characteristics can be multiplicative (what is multiplicative about waiting in an outbox?). We regard the why of the lognormal distribution for message delays as an unanswered question.

Can the results of this AUTODIN investigation be applied to any other system? According to the SAMSO study cited in Ref. 3 and in the Introduction to this report, their AUTOVON connection (33 outgoing lines) typically experienced several 10-minute blockages per day, and had blockages lasting three or four hours on as many as four days during the year. Counting three 10-minute blockages each 10-hour working day gives a probability of 5 percent that the AUTOVON connection is down for 10 minutes, and taking three blockages of three hours each in a 330 day year gives a probability of about 0.3 percent. The corresponding numbers for transit delays of Flash messages in AUTODIN (see Fig. 12, curve labeled Dry), are 2.5 percent and 0.05 percent, for transit delays of all messages in AUTODIN (Fig. 16, curve labeled Dry), are 16 percent and 0.5 percent. Thus, the normal delay on AUTOVON, at least for SAMSO (which is probably a high-quality center), is between that for Flash messages and all messages on AUTODIN, somewhat closer to Flash. The rain effect on transit delays on AUTOVON should be reasonably well described by shifting the curves of Figs. 12 and 13 upward to match the Dry curves to the AUTOVON data (the slopes are almost the same). Thus, the conclusions about transit delays on AUTODIN for Flash messages--real and significant effects during rain periods, no significant effects on an annual average basis--should be applicable to AUTOVON as well, with somewhat less effect on AUTOVON, since its inherent delays (at least for SAMSO, we have no information on other stations) are somewhat greater than those of AUTODIN. If we assume that AUTOVON has no administrative delays (it should have approval delays), then these conclusions apply to the total delays as well.

Looking at Figs. 12 and 13, we see that if an enemy could predict with sufficient accuracy the time of onset, duration, and intensity of rainfall, he might be able to secure an advantage if we used a millimeter-wave system for communication and did not employ redundancy. From Table 13, the mean duration at Island Beach of a rain rate exceeding 1 mm/hr is 8.7 minutes. Since storms typically travel at 50 km/hr,[18] this corresponds to a spatial resolution of about 7 km, which is within the capability of the Soviet METEOR meteorological satellite for observation in the visible spectrum.[28] The METEOR satellite makes 14 revolutions about the earth daily. A single satellite should see each point on the earth twice a day. The Soviets need two or three spacecraft operational at any one time to obtain full earth coverage daily. At present, they do a fair job of maintaining two in orbit, but not three. If we assume the satellite cameras can operate out to an angle of 30° from nadir, then they remain in view of a given point on the satellite track for 2.6 minutes. Thus, the satellite weather information, with two spacecraft six hours apart, would be four 2.6 minute sections of data in each 24 hours with respect to any point on the ground. Predicting the onset and duration of rain to an accuracy of 10 minutes with such data seems dubious, although it is conceivable. The potential advantage to an enemy cannot be assessed clearly but it does not appear great.

This completes our investigation of the effects of employing millimeter-wave links on the writer-to-reader delays in military communications systems. Section V gives the conclusions we can draw from this analysis.

V. CONCLUSIONS

The questions we have considered in this report are (1) What is the distribution of delays in military communications systems? and (2) How would this delay distribution be affected by the use of millimeter-wave links? From our analysis of AUTODIN I the following conclusions may be drawn:

- The administrative delays, especially time awaiting pickup at the destination station (T_6) and the destination local mail delivery time (T_7), provide by far the greatest contribution to the total delay. Efforts to reduce T_6 and T_7 would have much greater effect on decreasing the total delay time than would attempts to reduce the communications processing time or interstation transit time. If electronic deliveries were employed, even if only for unclassified traffic, the delays could be substantially reduced. This conclusion is the same as that found in R-2473-AF (Ref. 3), but is placed on a firmer foundation. We recognize that there may be major cost and manpower problems.
- For both Flash traffic and the complete message set, the time spent in interstation transfer (T_4) is by far the smallest of any of the seven time intervals. For AUTODIN I Flash traffic the contribution of T_4 to the total delay is at most a few percent of the total delay. For the complete message set, transit delay is only discernible for the 0.1 percent of the set that have the shortest delays, and they are only affected slightly.
- All time intervals can be well represented by broken-line lognormal distributions with very few changes in slope. This deduction applies both to Flash traffic and to the complete message set.
- There are no significant correlations between different intervals.

- The Flash traffic contains a large number of outliers (messages with delays over eight hours in some time interval). We have analyzed these as being almost entirely a result of messages being held overnight or through the weekend. Unless alternate message recipients are designated, there is no apparent way to improve this situation.
- Use of the Crane model permits us to compress the many parameters (frequency, receiver characteristics, elevation angle, geographical location, and season) into just four values of rain rate which bracket and describe the conditions.
- The distribution of rain duration is approximately lognormal.
- When we combine rain-induced delays and transit delays, we find that for Flash messages, the increase in transit delay is real and significant during rain periods, but only slight on an annual average basis. For the complete message set, the relative increase during rain periods is considerably smaller than for Flash, and the change is not significant on an annual average basis. We would expect that the effect of rain on an AUTOVON system employing millimeter waves would lie between AUTODIN Flash and AUTODIN complete.
- If we consider message total delays (combining ground, transit, and rain-induced), we find that the effect of the use of millimeter waves on the total delay for Flash messages is very slight during rain periods, and is negligible on an annual basis. The effect on the total delay for the complete message set is insignificant during rain periods and is indetectable on an annual basis.
- All these conclusions have been based upon a configuration which places millimeter waves in a most unfavorable light, with all the system traffic sent through millimeter-wave satellite links. System redundancy and the use of other communications media would reduce the effects of rain-induced delays considerably.
- Certain military communications systems, such as dedicated command and control links, should not rely solely on millimeter

waves. For other systems, such as the mass traffic AUTODIN system, we believe that the analysis of this report demonstrates that the effects of rain on the distribution of delays are sufficiently slight, when considered in the proper context, that they do not provide a reason to forego the several advantages of millimeter waves.

APPENDIX

For completeness, we present in this appendix the delay distributions for the several time intervals for Operational Immediate, Priority, and Routine traffic. Figures A1 through A6 show the distributions for outgoing, transit, and incoming delays for each of these precedence categories. We do not analyze this material further, except to note that the distributions for Operational Immediate and for Priority traffic lie between Flash and the complete distribution, whereas Routine traffic is not handled as rapidly as the complete distribution, as would be expected. The number of records used to obtain the curves of Figs. A1 through A6 are listed in Table A-1.

Table A-1

NUMBER OF RECORDS PER TIME INTERVAL

Time Interval	Immediate	Priority	Routine
T_1 - Approval	1956	28,370	104,851
T_2 - Delivery to TCC	3025	40,158	122,931
T_3 - Processing in TCC	3070	42,059	126,330
T_0 - T_1 and T_2 and T_3	1659	27,530	92,165
T_4 - Transit	688,750	1,913,945	2,695,720
T_5 - Processing in TCC	8490	166,889	300,556
T_6 - Awaiting pickup	8138	165,531	297,891
T_7 - Local delivery	7910	156,073	286,267
T_I - T_5 and T_6 and T_7	6613	135,141	253,339

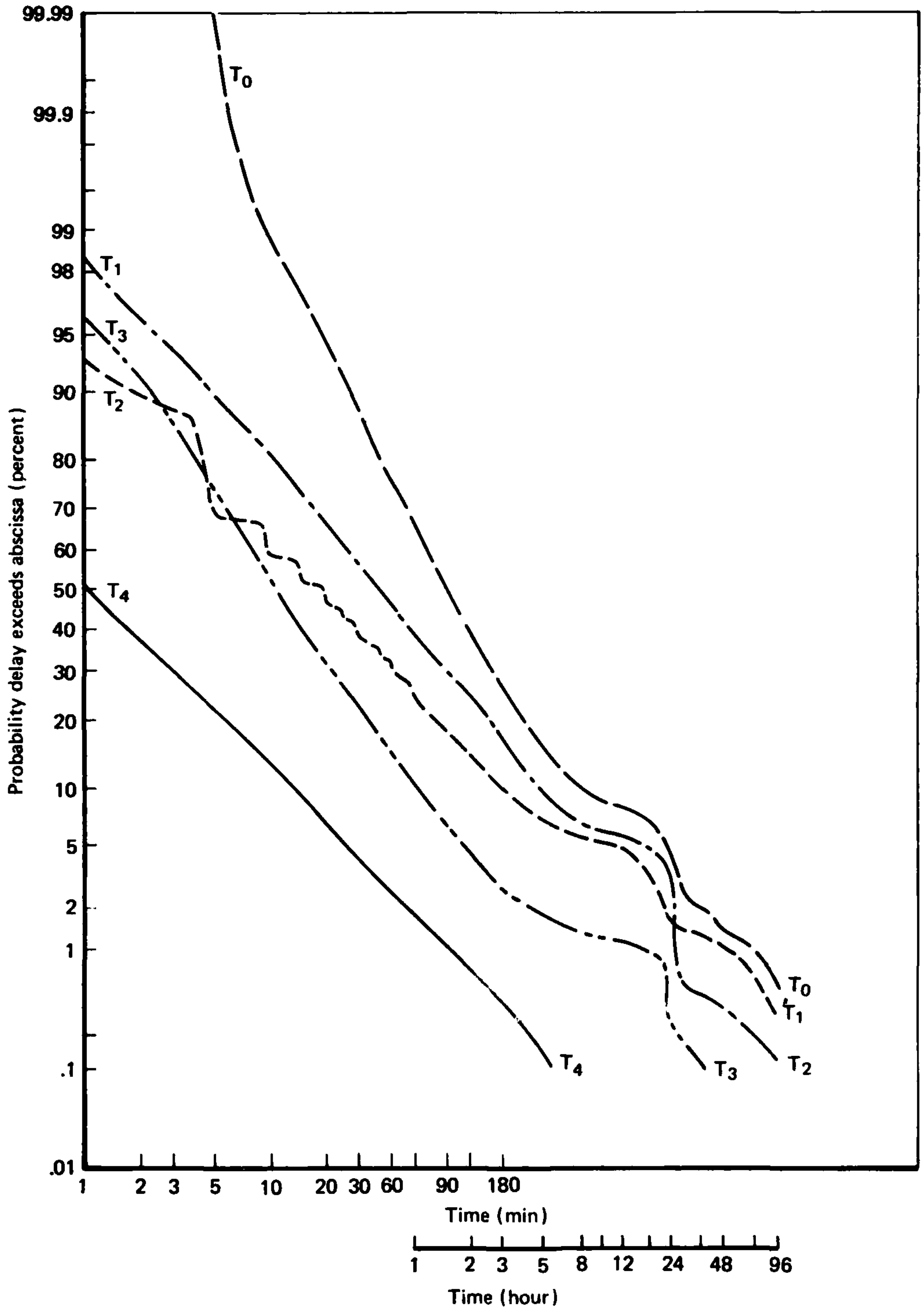

Fig. A1—Probability distribution of handling times—outgoing Immediate messages

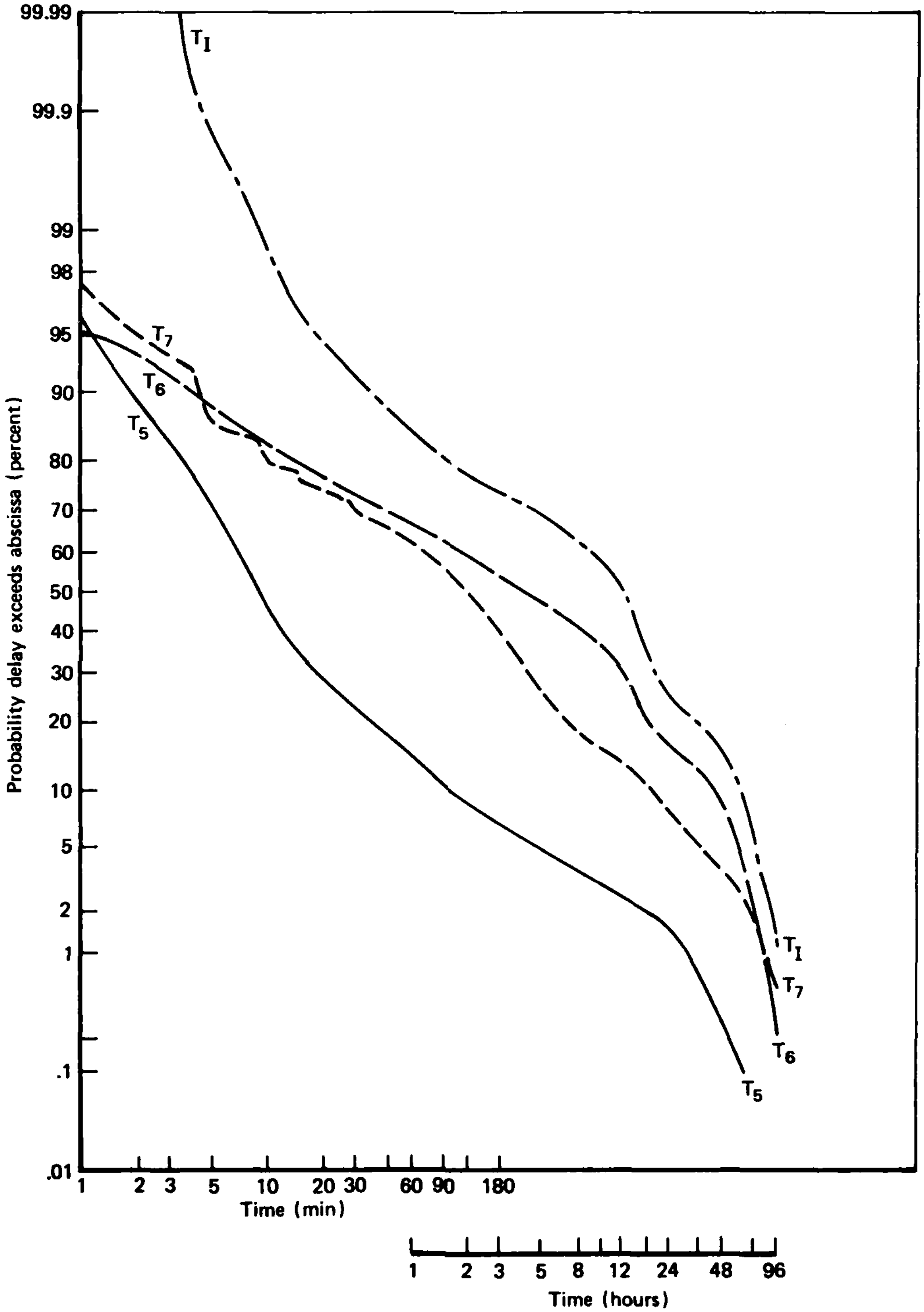

Fig. A2—Probability distribution of handling times–incoming Immediate messages

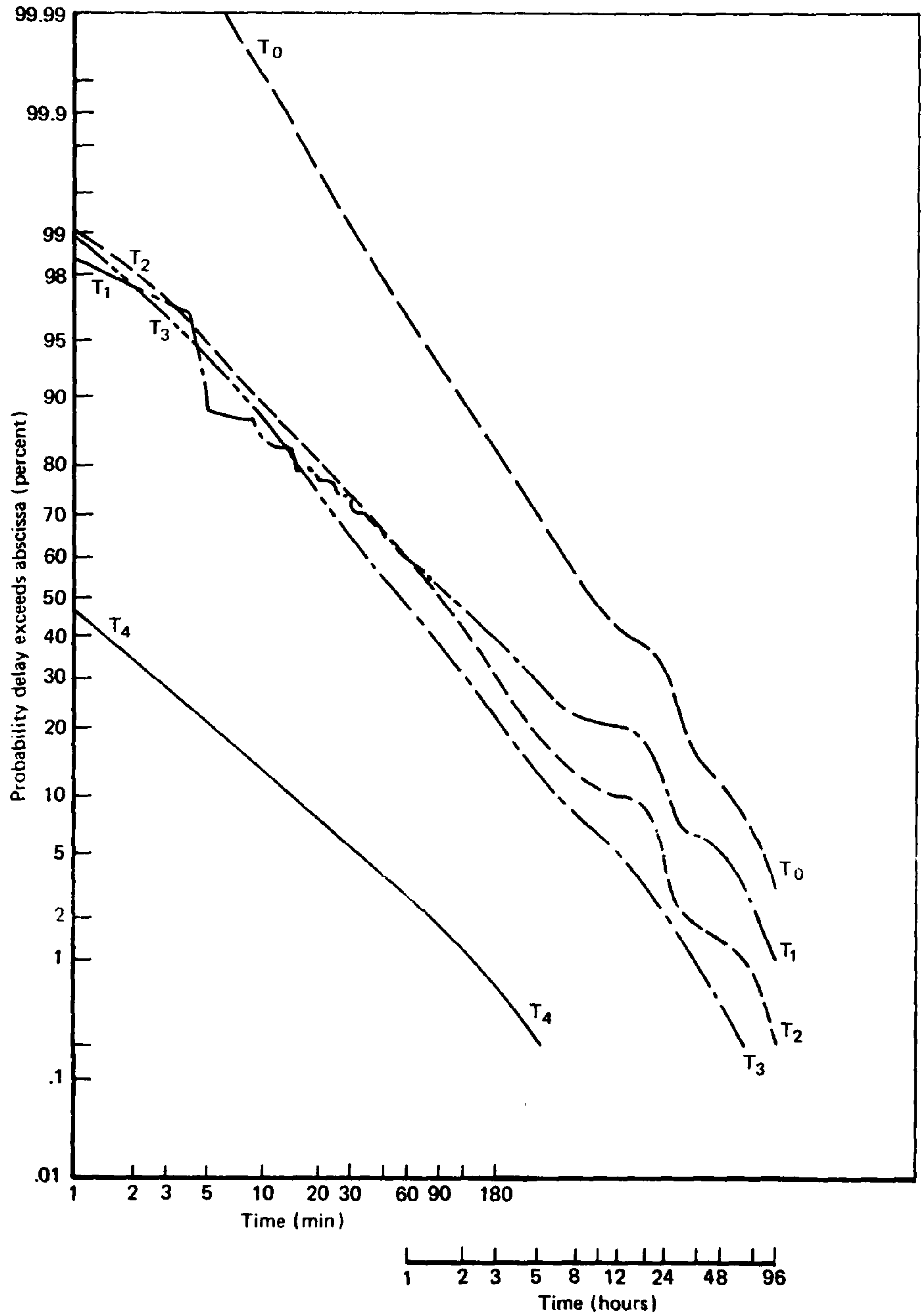

Fig. A3 — Probability distribution of handling times — outgoing Priority messages

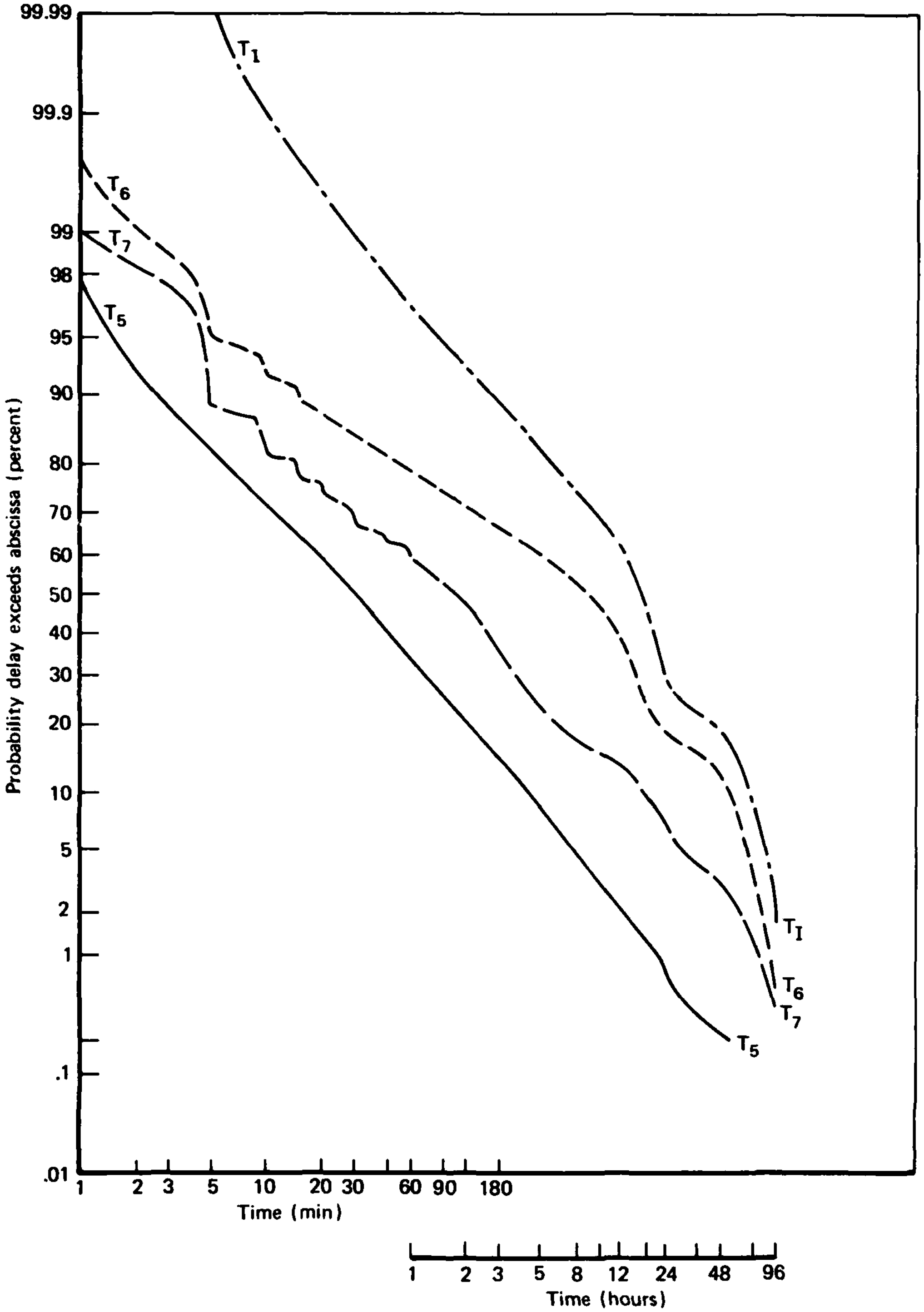

Fig. A4 — Probability distribution of handling times—incoming Priority messages

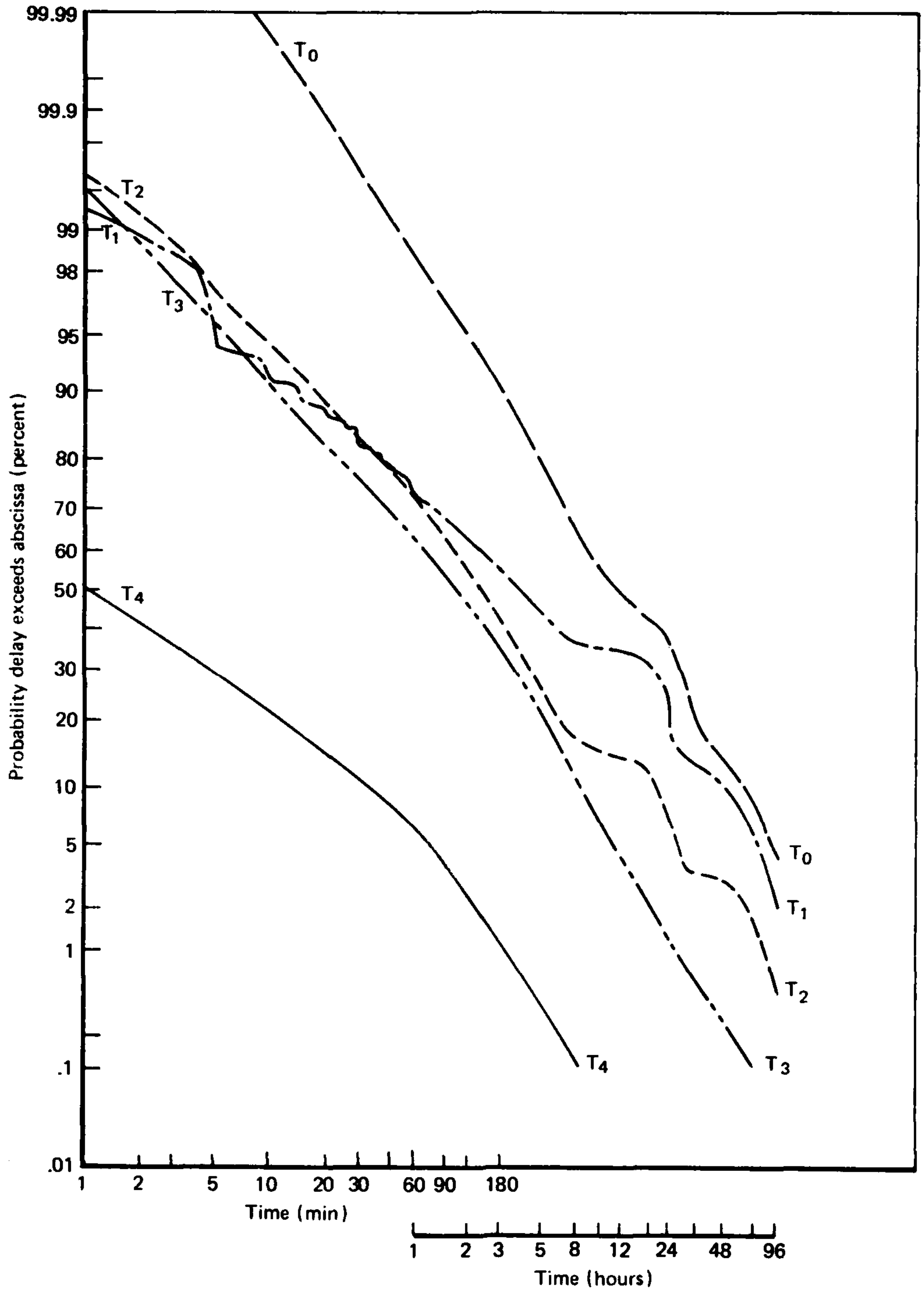

Fig. A5—Probability distribution of handling times—outgoing Routine messages

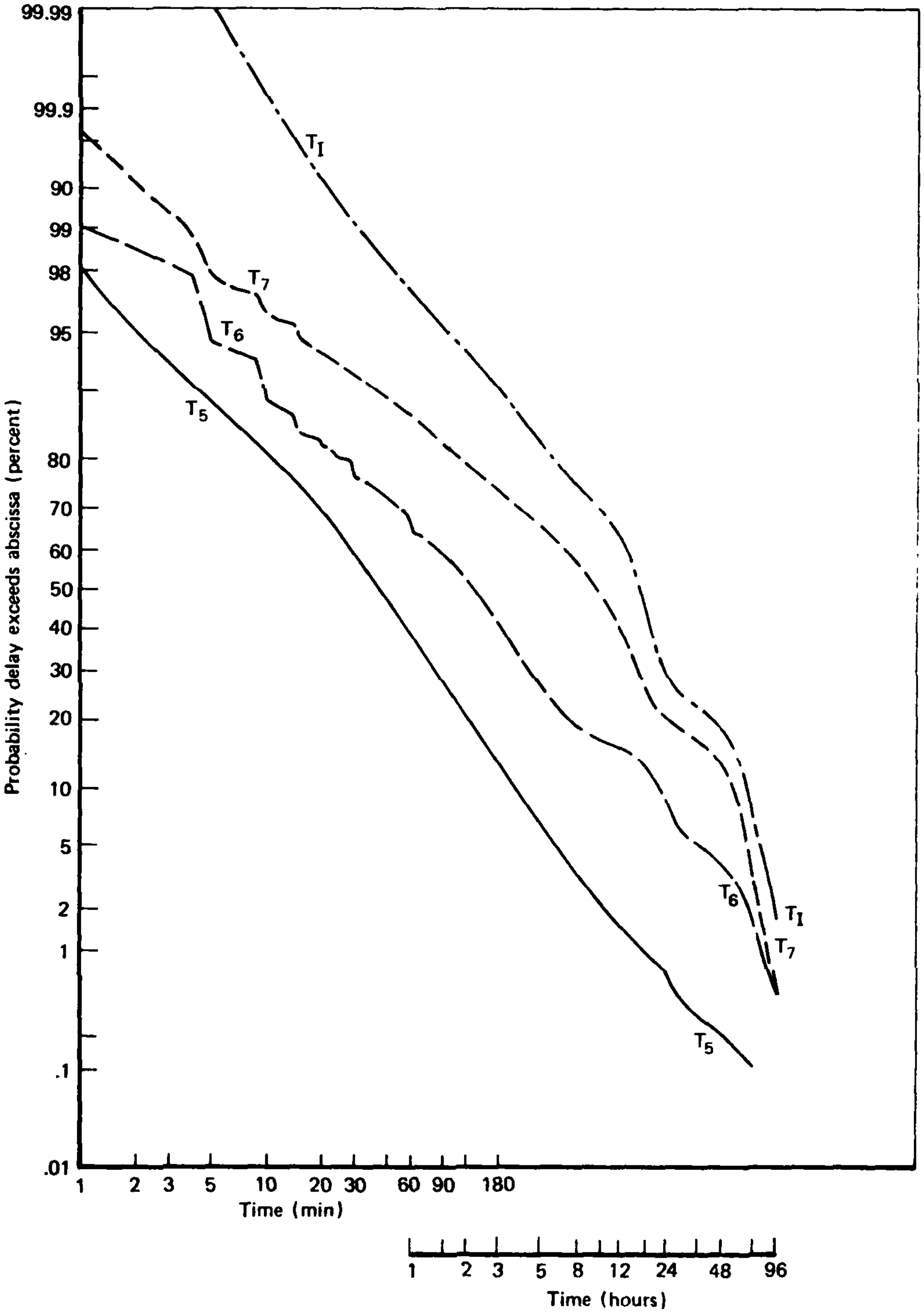

Fig. A6 — Probability distribution of handling times – incoming Routine messages

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